King County Brightwater TREATMENT SYSTEM

Brightwater Marine Outfall Puget Sound Marine Modeling Report

November 2002

King County
Department of Natural Resources and Parks
Wastewater Treatment Division

Brightwater Treatment System

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EXECUTIVE SUMMARY

As part of the Regional Wastewater Services Plan, King County plans to construct a new regional wastewater treatment facility in north King County or South Snohomish County by 2010. The treatment plant will have an outfall in the northern part of Puget Sound between Richmond Beach and Edmonds. Currents will dilute and distribute the discharged effluent within and out of this part of the Sound. Therefore, it is important to understand the flow of water in this area and how the effluent is diluted. To augment field studies of physical oceanography, King County, in cooperation with the University of Washington, created a numerical circulation model of this region. This report describes the development and application of this numerical model to predicting the water circulation patterns in Puget Sound, and specifically in the region of the proposed outfall.

The circulation model of Puget Sound was based on the Princeton Ocean Model (POM), a primitive equation ocean model, which has an extensive history of use for modeling of estuaries, coastal regions, and open oceans. The model includes all of Puget Sound at a 600 m by 900 m grid resolution, and extends into the Strait of Juan de Fuca as far as the southern tip of Vancouver Island. A number of modifications were made to the model, including the addition of atmospheric coupling, river inflows, and an advanced advection-dispersion algorithm, to simulate processes important within Puget Sound.

The model was used to predict effluent advection and dispersion under summer and winter scenarios for each of three zones representing potential locations to site a diffuser to discharge treated effluent from the proposed treatment plant. The model simulated an effluent discharge at the bottom of Puget Sound and traced the effluent for a 10-day period. The minimum dilution at eleven shoreline locations, which correspond to popular shoreline sites, is reported. Similarly, the minimum dilution predicted along the bottom of Puget Sound is reported. These dilution values were combined with a separate estimate of the long-term dilution to estimate the potential additional contribution of the proposed outfall toward the concentration of conservative substances within Puget Sound.

The model predicted that the discharged effluent plume would generally remain in the lower portion of the water column, and very low concentrations would reach shoreline locations within 10 days. Including the long-term accumulation of effluent in Puget Sound, dilutions of no less than one part effluent in 1750 parts water were predicted to reach shoreline locations. The dilution near the seafloor, where the effluent plume reaches the bottom, was predicted at more than 340:1. These predictions show that the proposed discharges have very high levels of dilution and are likely to receive significant additional dilution before reaching the shoreline sites.

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Acronym & Abbreviation List

ADCP	Acoustic Doppler Current Profiler
^{o}C	degrees Centigrade
cm/s	centimeters per second
CFL	Courant-Friedrichs-Lewy
DEM	digital elevation model
ft	Feet
m	Meters
MGD	Million Gallons per Day
MLLW	Mean Lower Low Water
MSL	Mean Sea Level
NOAA	National Oceanographic and Atmospheric Administration
POM	Princeton Ocean Model
SEPA	State Environmental Policy Act
UTM	Universal Trans-Mercator
WTD	Wastewater Treatment Division
WQS	Water Quality Standards
WQC	Water Quality Criteria
ZID	Zone of Initial Dilution

1.0 INTRODUCTION

1.1 The Brightwater Marine Outfall Siting Process

In November 1999, the Metropolitan King County Council approved the Regional Wastewater Services Plan to upgrade King County's existing regional wastewater system (King County Ordinance 13680, Nov. 23, 1999). Included in this plan is the construction of a new regional wastewater treatment plant (WWTP) in either northern King or southern Snohomish County by 2010. The new treatment plant will have a marine outfall to discharge treated effluent to Puget Sound in either northern King or southern Snohomish County.

Using King County Council-adopted policy siting criteria, the County conducted two phases of outfall site analysis in 2000 and 2001. These policy siting criteria were used to identify suitable locations for the outfall and diffuser in northern King and southern Snohomish counties. At the conclusion of the second phase of outfall site selection, the King County Council accepted four candidate marine outfall zones, 5, 6, 7N, and 7S, for further analysis and review (King County Ordinance 14278, Dec. 13, 2001; Figure 1). Each zone contains one potential diffuser site with the exception of Zone 7S, which contains two. Reports produced from the siting studies should be consulted for complete details of the Phase 1 and Phase 2 outfall site selection process to date (King County 2001a, b, and c).

Further evaluation of the approved candidate outfall zones identified outfall Zones 6, 7N and 7S diffuser site B as the strongest alternatives for the outfall and diffuser (King County 2002). These outfall zones were identified as feasible alternatives based on land availability for construction, construction conflicts with other public services, and differences in the bathymetry and currents among the outfall zones.

1.2 Hydrodynamic Modeling Objectives

The goals of this modeling effort were to provide both quantitative and qualitative estimates of the expected far-field effluent transport and dilution within Puget Sound. Specifically, predictions were desired to answer:

1) What is the predicted effluent dilution at shoreline areas of Puget Sound in King and Snohomish Counties?

2) What is the minimum predicted effluent dilution near the bottom of Puget Sound?

3) What is the initial effluent dilution at the initial and regulatory mixing zones?

In addition, the modeling effort was anticipated to be able to extrapolate the oceanographic observations to times for which no observations are available.

This report focuses on the modeling effort to predict the distribution and dilution of effluent after the initial plume dilution. Estimates of the initial plume dilution under a variety of conditions are discussed in a separate report (West Consultants and King County 2002).

1.3 Overall Modeling Approach

Three separate models were chosen to simulate the effluent discharge and Puget Sound circulation. EPA's PLUMES model was chosen to simulate the effluent plume, initial dilution zones and plume dynamics. The application of this model is described separately (West Consultants and King County, 2002). In conjunction with the University of Washington, the Princeton Ocean Model (POM) was selected to model the general circulation of Puget Sound for durations of days to weeks. A published model (Cokelet et al. 1991) of the annual mean circulation was chosen to simulate the long term, annual average, distribution of tracers within the Sound.

The focus of this report is the mesoscale POM model, which models the time variation of currents, salinity, temperature, and tracers within Puget Sound. The model's relationship to the oceanographic field observations and the other two models is described below.

1.3.1 Oceanographic Observations

An extensive program was undertaken to measure oceanographic properties in Puget Sound between July 2000 and January 2002. The study focused on the region of Puget Sound known as the Triple Junction, reflecting the convergence of Admiralty Inlet, Possession Sound, and the Main Basin. This region extends north from Seattle to the southern end of Whidbey Island. Observations included current meters, drift cards (floating post-card-sized drifters), drogues (underwater sails), and dye (used as a water flow tracer). As part of King County's study:

- Nine current meters were moored at 56 locations,
- 6100 drift cards were released at 18 locations,
- 103 drogues were deployed at 13 locations,
- Five dye studies were conducted.

These observations are described and discussed in *Final Report: Puget Sound Physical Oceanography Related to the Triple Junction Region* (Ebbesmeyer et al., 2002). Figure 2 illustrates the current meter deployment locations.

1.3.2 Computer Dilution Modeling

Three computer models were used to predict the effluent dilution at locations and distances corresponding to three different time-scales. This report focuses on the implementation and results of only one of these models, the Princeton Ocean Model. The other two models are discussed briefly as related to this project.

1.3.2.1 PLUMES Dilution Modeling

The PLUMES modeling package is distributed and maintained by the EPA's Center for Exposure Assessment Modeling, and is freely available (http://www.epa.gov/ceampubl/swater/plumes/). The modeling package contains two initial dilution plume models (RSB and UM). These models are intended for use with plumes discharged to marine and some freshwater bodies. Both buoyant and dense plumes, single sources, and many diffuser outfall configurations can be modeled.

These models simulate the initial dilution of a discharge due to mixing with the ambient environment driven by the discharge's initial buoyancy and momentum. Two algorithms are included with the PLUMES package to estimate dilution beyond the zone of initial dilution. King County used these models to predict dilution at the zone of initial dilution (ZID), the regulatory chronic and acute mixing zones, as well as the plume trapping depth under a range of potential scenarios. The conditions and results of these simulations are described in *Phase 3 Initial Dilution Assessment of Potential Diffuser Zones* (West Consultants and King County 2002).

1.3.2.2 POM Dilution Modeling

The Princeton Ocean Model (POM, http://www.aos.princeton.edu/WWWPUBLIC/htdocs.pom/) is a sigma coordinate, free surface, primitive equation ocean model, which includes a turbulence sub-model. This model has an extensive history of use for modeling of estuaries, coastal regions, and open oceans.

A sigma coordinate model discretizes the vertical domain on a terrain-following coordinate ("sigma" coordinate). In this approach, the sigma coordinate represents a fixed fraction of the depth. Geopotential (Cartesian or z-) coordinates are the most commonly applied alternative approach, where model layers remain essentially horizontal and more layers are needed to represent deeper portions of the domain.

A free surface model allows the height of the water surface to vary throughout the model, and thus allows gravity waves to propagate. Since gravity waves propagate relatively quickly, a mode-splitting technique is used to provide a two-dimensional gravitation wave solution at a separate timescale from the three-dimensional "internal" solution.

A primitive equation ocean model refers to a class of models that solve a governing set of coupled, nonlinear partial differential equations to obtain the time-dependent behavior of circulation in the ocean. These governing equations are the Navier-Stokes and continuity (conservation of mass) equations, combined with conservation equations for the scalar quantities of temperature, salinity, turbulent kinetic energy and tracer concentrations.

In order to provide a tractable set of equations, several assumptions are used. The Navier-Stokes equations are replaced with the Reynold's averaged form, in which the turbulent fluctuations are represented as a stress. The turbulence sub-model is used to parameterize the unknown turbulent stresses and diffusion terms that arise.

The model also incorporates the hydrostatic approximation, which assumes that vertical momentum is small and prescribes an exact balance between gravity and the vertical pressure gradient. The Boussinesq approximation is used, which neglects changes in the mass or inertia of a water parcel due to changes in the ambient density.

For this application, additional code was added to the POM to provide a coupling to atmospheric conditions. This allows inclusion of wind forces on the surface, as well as solar and ambient heating and cooling of the water surface.

To use this model to simulate effluent dilution, additional tracers were included in the model. The tracer could be released at a specific location (model cell) or distributed vertically through the water column according to the estimated trapping depth of a diffuser discharge. The subsequent concentrations within various model cells are divided by the initial effluent concentration to compute dilution values.

This model computes tracer movement from an initial state, progressing forward in time. Small errors in the short term flow pattern can compound to create a significant error in the annual mean circulation. For this reason, the Basin Scale model was used to predict steady-state dilutions, and these steady-state dilutions were combined with the POM model results to predict dilutions near the diffuser and to estimate plume dilutions for periods of up to several weeks.

1.3.2.3 Basin Scale Dilution Modeling

The Basin Scale model was developed by Cokelet et al. (1991) and represents Puget Sound as a number of basins with the exchange rate defined between them. Each basin is separated into two vertical layers (boxes), and the annual mean flow between boxes was determined from conservation equations for salinity and copper. Since this model was developed and calibrated to data representing the long-term distribution of chemicals within Puget Sound, it was used to estimate the steady-state distribution of effluent/tracers.

1.4 Report Organization

This report presents predicted effluent dilutions throughout Puget Sound for a range of discharge and receiving water conditions. The report is divided into seven sections. Section 1 presented the context of the siting process, and the objectives and approach of the marine modeling effort. In Section 2, a brief background of the physical characteristics of Puget Sound, the selection of discharge zones and shoreline use areas is provided. Section 3 outlines the POM model configuration and inputs functions. The calibration procedures and verification of the model predictions are given in Section 4, along with a discussion of model uncertainty. In Section 5, we discuss the model scenarios and the predicted dilution results. Section 6 is a summary of these results and some conclusions are drawn. Section 7 is a list of references.

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2.0 BACKGROUND

The following subsections detail the physical characteristics and assumptions made to develop the POM model of Puget Sound.

2.1 Physical Characteristics of Puget Sound

Puget Sound is a deep, glacially carved fjord that connects to the Strait of Juan de Fuca through Admiralty Inlet and Deception Pass (Figure 3). The Strait of Juan de Fuca opens into the North Pacific Ocean between Washington State and Vancouver Island. Within the Sound, shallower sills (underwater shallow bars) separate a series of deeper basins.

The Main Basin extends from Tacoma to the south end of Whidbey Island in a north-south orientation. Depths in the basin exceed 280 m (700 ft), and are generally uniform across the center portion of the basin, with steep side slopes that level off near the shoreline. Vashon and Maury Islands divide the southern portion of the Main Basin into the East Passage and Colvos Passage.

To the south, South Sound is connected to the Main Basin by Tacoma Narrows. South Sound is generally shallower than the Main Basin, with regions of tidal flats and numerous finger inlets and embayments.

At the north end of the Main Basin, Possession Sound forms one branch of the Triple Junction, leading northward to Port Susan, Saratoga Passage, and Skagit Bay. While much of Port Susan and Saratoga Passage is similar to the Main Basin, with depths near 200 m (600 ft) and steep side slopes, extensive tidal flats also exist. The three largest rivers (by volume) in Puget Sound, the Skagit, Stillaguamish, and Snohomish, empty into Skagit Bay, Port Susan and Possession Sound, respectively (Figure 3). Skagit Bay is also connected to the Strait of Juan de Fuca by Deception Pass, a narrow, shallow passageway less than 500 m wide.

Hood Canal extends southward from the middle of Admiralty Inlet, almost reaching South Sound. This long narrow basin has depths greater than 200 m, becoming shallower further south. A sill about 50 m deep separates Hood Canal from Admiralty Inlet.

2.2 Brightwater Discharge Options

Using the Brightwater policy site selection criteria adopted by the King County Council in 2001, King County included two treatment plant sites and three outfall sites to be included in the State Environmental Policy Act (SEPA) scoping notice for the Brightwater EIS (King County, 2001a,b,c). The projected average wet weather flows (AWWF) flows from the treatment plants are estimated at about 36 million gallons per day (MGD), increasing to 54 MGD after a plant expansion occurring around 2040. The draft EIS also evaluates a sub-alternative at the Unocal site, that of a 72 MGD-plant to include local flows from Edmonds and Lynnwood.

The three outfall termini are located within Zones 6, 7N, and 7S, with Zone 6 off Edwards Point at the south end of Edmonds, and Zones 7N and 7S to the north and south of Point Wells, respectively (Figure 1).

2.3 Shoreline Use Areas

King County conducted a study to evaluate the types and frequency of human use of the shoreline (King County, 2002). The study identified the major locations of public access and use of the shoreline. Eleven of these locations, shown in Figure 4, were selected as the locations to model near-shore and near-surface dilutions from the proposed outfalls. These dilution estimates were incorporated into an evaluation of potential impacts associated with a new marine outfall (King County, 2002).

3.0 MODEL CONFIGURATION

This section presents the hydrodynamic and transport model being used (POM). A summary of model characteristics are given, and the model inputs are described.

3.1 Description of the POM model

The Princeton Ocean Model is a three dimensional ocean circulation model freely available from its developers at http://www.aos.princeton.edu/WWWPUBLIC/htdocs.pom. This section presents a summary of the original model and the enhancements made to apply the model to Puget Sound.

3.1.1 POM model

The Princeton Ocean Model is a three dimensional, numerical model intended for use in modeling oceanic and coastal circulation. The model is a sigma coordinate, free surface, primitive equation ocean model, and includes a turbulence sub-model. According to the users manual, the principle attributes of the model are:

- An imbedded second moment turbulence closure sub-model to provide vertical mixing coefficients

- A sigma coordinate model in that the vertical coordinate is scaled on the water column depth

- The horizontal grid uses curvilinear orthogonal coordinates and an "Arakawa C" differencing scheme.

- The model has a free surface and uses a mode-splitting scheme. The external mode solves the two-dimensional depth-averaged equations explicity and uses a time step based on the Courant-Friedrichs-Lewy (CFL) condition and the gravity wave speed. The internal mode solves the three-dimensional vertical difference equations implicity and permits use of fine vertical resolution in the surface and bottom boundary layers.

- Complete thermodynamics have been implemented.

The POM user guide contains information on the form of equations solved in the model, as well as the numerical solution technique.

3.1.2 Enhancements to POM model

Several modifications were made to adapt the model to simulate tracer transport in Puget Sound. This section briefly describes the modifications made to the POM model.

Advection Scheme

The central difference advection scheme was replaced by a total variance-diminishing (TVD) scheme. The Smolakiewiez multidimensional positive definite advection transport algorithm

(MPDATA) was used, as coded by G. Sannino and V Artale (Smolarkiewicz, 1984). This is available through the POM web site.

Fresh Water Inputs

To simulate river discharges into Puget Sound, the code was modified to allow fresh water inputs. This was implemented as a subroutine based on the code available from the POM website authored by J. Berntsen, Institute of Marine Research, Norway. M. Kawase, University of Washington Department of Oceanography, modified this code to simplify argument passing. Further modifications were made to ensure conservation of heat and salinity.

Atmospheric Coupling

The basic POM model provides for the possibility of atmospheric coupling through terms for the surface shear stress, heat flux and salt flux. M. Kawase provided additional code to convert standard atmospheric observations of wind speed and direction, precipitation, relative humidity, air temperature, and solar radiation into these surface terms. The solar radiation term was subsequently split into incoming solar radiation and a net long-wave radiation.

Additional Tracers

The basic POM code implements two tracers, temperature and salinity. The code was modified to allow an unlimited number of additional tracers to be tracked within the model.

3.2 Hydrodynamic Model Input Functions

This section discusses the model input files and configuration used to simulate Puget Sound. The model configuration is discussed in five components: a) the computational grid, b) the boundary tides, c) the time varying water quality constituents at the tidal boundary, d) the freshwater inflow rates and constituents, and e) the meteorological data for surface heat exchange and surface wind shear.

3.2.1 The Computational Grid

A Cartesian grid of rectangular elements, 600 m East-West by 900 m in the North-South direction, was used to discretize the horizontal geometry of Puget Sound. The horizontal mesh was constructed from a projection of Puget Sound in Universal Trans-Mercator (UTM), originating at (5209305, 486555), and extending for 121 cells eastward and 175 cells northward. The mesh is shown in Figure 4.

Bathymetric data for Puget Sound were obtained from the National Oceanic and Atmospheric Administration (NOAA, http://sposerver.nos.noaa.gov/bathy/pacific.htm) as a 30-m digital elevation model (DEM) in UTM coordinates. Bathymetric data for the Strait of Juan de Fuca were obtained from the University of Washington, at a 300-m horizontal resolution. The average depth of each element of the computational grid was computed from averaging the bathymetric data within the element. When more than 50 percent of the area within an element was above Mean Sea Level (MSL), the cell was set to above MSL.

Model cells that had an average depth of less than 4 m were set to a depth of 4 m to allow a finite depth of water to be present in those cells under the lowest tidal condition.

Deception Pass is a narrow channel connecting the north end of Whidbey Basin to the Strait of Juan de Fuca. With an east-west orientation, Deception Pass is significantly narrower than the 900 m model cell dimensions. The model grid dimensions were reduced to obtain the correct flow characteristics. Measurements from Lavelle et al. (1988) of the flow rate vs. elevation difference across Deception Pass were used to determine the appropriate cell dimensions.

The water column in each cell was divided into fourteen layers. With the exception of the top three layers, each layer represented 8.3% ($1/12^{th}$) of the water depth. The vertical resolution was finer in the top three layers to improve the representation of the freshwater layer and wind-driven surface currents. The thickness of the top layer was 1% of the water depth, the second 3%, and the third 4%.

3.2.2 Tidal Elevation

The model is coupled to the Strait of Juan de Fuca, and thus the Pacific Ocean, at an open boundary along portions of the northern and western grid boundary. A radiation-type boundary condition is applied here. A uniform tidal elevation is set at each timestep along both the north and west boundary. The boundary elevation is computed from a seven term harmonic series representing the M2, K1, N2, O2, S1, P1, and M4 tidal harmonics. These tidal harmonics have known frequencies (NOAA, http://www.co-ops.nos.noaa.gov/data_res.html), while the tidal amplitudes and relative phases were specified to produce agreement with the Seattle tide gauge.

3.2.3 Major Fresh Water Inputs

Sixteen major rivers are included as fresh-water sources into the model. Each river adds a volume of fresh water (salinity = 0) into the model at each timestep, based on daily river flows. Gauged river flows were obtained from the USGS, and modified according to Lincoln (1977) to account for ungaged drainage. The rivers used in this model are listed in Table 1 and their locations within the model are shown in Figure 5.

Table 1.
Major Rivers included in Puget Sound Model

River	Puget Sound Basin	Annual Flow (cfs)
Deschutes	South Sound	802
Dosewallips	Hood Canal	724
Duckabush	Hood Canal	494
Duwamish/Green	Main Basin	1790
Hamma Hamma	Hood Canal	586
Nisqually	South Sound	2761
Small rivers in the Port Townsend area	Admiralty Inlet	272
Puyallup	Main Basin	3756
Quilcene	Hood Canal	607
Sammamish/Cedar	Main Basin	1689
Shelton	South Sound	1063
Skagit	Whidbey Basin	16035
Skokomish	Hood Canal	1198
Snohomish	Whidbey Basin	9643
Stillaguamish	Whidbey Basin	4316
Small rivers in the Tacoma area	South Sound	311

3.2.4 Meteorological Data

Atmospheric data recorded at the University of Washington's Atmospheric Sciences Building were coupled to the model's surface layer. The data were applied uniformly over the entire model domain. The data were processed to remove gaps in the series and combined into 1-hour intervals. The original data were recorded at 1-minute intervals.

Wind speed and direction were decomposed into north and easterly components, and then averaged to form 1-hour averages.

Short-wave solar radiation, relative humidity, and air temperature were arithmetically averaged to form 1-hour means. No measurements of net long-wave radiation were available, so an annual average value of 65 W/m^2 was assumed.

Precipitation data were integrated to form 1-hour totals, then converted into metric units.

The atmospheric data used for the modeling runs discussed in this report can be found in Appendix A

3.2.5 Boundary Constituent Data

Temperature and salinity observations at three stations near the model's western boundary in the Strait of Juan de Fuca were obtained from the research consortium, JEMS. JEMS, the Joint Effort to Model the Straits, measured CTD profiles at monthly to bimonthly intervals at three stations along a line extending northward from Port Angeles. The most southerly station was used to force the model, and was applied to all boundary cells. The model interpolated between observation times to provide temperature and salinity values along the boundary. More information on the JEMS program and available data can be found at http://www.ecy.wa.gov/programs/eap/mar_wat/mwm_intr.html.

3.3 Effluent Simulation

A conservative tracer was implemented within the model to simulate an effluent discharge. Conservative tracers were used to provide dilution estimates for inert chemicals that are not degraded or otherwise removed from the water column. Chemicals or pathogens that decay or dye off in marine waters would be expected to have lower concentrations (higher effective dilutions) than the conservative tracers. Discharges from other effluent sources (other WWTP discharges, industrial discharges, etc.) were not included in the modeling. Instead, their contribution was included in the existing water quality and measured through an ambient sampling program (King County 2001d, 2002b). The model predictions were added to the existing chemical conditions in analyzing the potential impact to water quality (King County, 2002c).

An input file allowed specification of the timing of the discharge, the discharge rate, horizontal position, and either vertical position of the discharge, or the length of a diffuser along the seafloor. The discharge rate was assumed to be constant throughout the discharge interval.

If a diffuser length is input, the tracer can be distributed equally into the vertical layers that were within the predicted plume thickness, as determined from the equations given in Roberts et al. (1989). Since the horizontal dimensions of the model cell, at 600m by 900m, is much larger than the extent of the initial mixing zone, equations for plume dilution could not be used. Rather the appropriate mass of effluent tracer was added to the cell each timestep. This approach has the potential to under-predict the maximum concentrations by initially diluting the tracer throughout the entire cell. This is most likely to impact dilution estimates within a few cells of the discharge, in which case a dilution estimate from the PLUMES model may be more appropriate. Since a continuous release is being modeled for multiple days, the model is expected to be able to provide a reasonable estimate of the effluent dilution.

The simulations were run with a single discharge rate of 3 m^3/s (68 MGD) of tracer with an initial concentration of 100 (arbitrary units). Dilutions corresponding to other discharge rates were calculated from the same model simulation by scaling the initial concentration to maintain the original mass loading rate. Thus a discharge of 2.25 m^3/s (45 MGD) would result in an initial concentration of 133 (100*3/2.25 arbitrary units). This produces the same dilution and advection within the model, as the tracer is added to each cell as a mass flux. However, the initial vertical distribution of tracer within the water column is affected by changes in the flow rate, independent of the tracer concentration. Thus for flow rates greater than 3 m^3/s, the model results are likely biased towards too much tracer in the lower water column, while flow rates less than 3 m^3/s likely have too much tracer in the upper water column.

4.0 HYDRODYNAMIC MODEL CALIBRATION AND VERIFICATION

The following sections describe the calibration of the model and the comparison of model results to appropriate observational data. The model was "calibrated" by specifying the open boundary tidal forcing to match the Seattle tide gauge using 1997 data. Friction parameters were specified to match the model with South Sound tide gauges. This calibration was verified by comparing the model tidal predictions with 2000 data to the observations. Further verification was obtained by comparison with 28-day mean velocity profile obtained for three cross-sections through Puget Sound.

4.1 Calibration Procedures

A primitive equation ocean model, such as POM, computes most variables from governing equations, leaving relatively few parameters to be adjusted in calibration. The major adjustments made to the model reflect the lack of data available to adequately describe the boundary conditions. The tidal amplitude and phase was constructed to enable the model to fit the Seattle tide gauge, while the bottom roughness and horizontal mixing were selected to give the best fit to a number of tide gauges throughout Puget Sound. The mixing depth of the freshwater river inflows was adjusted to improve the fit to salinity data in Whidbey Basin. Otherwise, the model was run with default parameters.

To calibrate the open boundary tidal forcing, the model was run for 30 days to "spin up" the model starting on January 1, 1997. The next 60 days of simulation were used to record predicted free surface elevations at the grid cell nearest the Seattle tide gauge in one-hour intervals. A least-squares algorithm was then used to fit a seven frequency harmonic series to this time series, with the harmonic frequencies fixed at the tidal phase speeds. This resulted in tidal amplitudes and phases, which were compared to the NOAA statistics for the Seattle tide gauge. The boundary forcing values were adjusted, and the process repeated until satisfactory agreement was obtained.

The bottom friction parameters and horizontal mixing coefficient were adjusted together to vary the effective speed of the tidal wave (Table 2). Tidal harmonics were compiled by Lavelle et al. (1988) for 51 stations throughout Puget Sound. Forty-nine of these are represented in the model (Figure 6), and were used for this calibration. The seven tidal harmonics and phases were determined from the 60 day run, and compared with the published observations. The parameters were adjusted, and the model re-run until suitable agreement was obtained. If these changes affected the calibration with the Seattle tide gauge, the boundary forcing was adjusted to account for this. Since only seven harmonic frequencies were simulated in the model, and a number of the tide gauges were deployed for short periods of time (one month or less), differences of a few centimeters of tidal amplitude or a few degrees of phase angle were considered to be acceptable and within the underlying uncertainty of observations.

The mixing depth of the freshwater inflows was adjusted to provide a less saline surface layer of similar thickness to that observed by Ecology's CTD casts at stations SAR003 (Saratoga Passage

– East Point) and PSS 019 (Possession Sound – Gedney Island). This CTD data was obtained from http://www.ecy.wa.gov/programs/eap/mar_wat/mwm_intr.html.

Table 2.
Model Parameters Specified in Calibration.

Parameter Description	POM Symbol	Value
M2 tidal harmonic amplitude (m)	ampM2	0.6777
K1 tidal harmonic amplitude (m)	ampK1	0.7157
S2 tidal harmonic amplitude (m)	ampS2	0.1690
N2 tidal harmonic amplitude (m)	ampN2	0.1466
O1 tidal harmonic amplitude (m)	ampO1	0.4053
P1 tidal harmonic amplitude (m)	ampP1	0.206
M4 tidal harmonic amplitude (m)	ampM4	0.03246
M2 local tidal phase, in radians from 1-1-1997	epochM2	1.8089
K1 local tidal phase, in radians from 1-1-1997	epochK1	-2.2686
S2 local tidal phase, in radians from 1-1-1997	epochS2	-1.7752
N2 local tidal phase, in radians from 1-1-1997	epochN2	4.6726
O1 local tidal phase, in radians from 1-1-1997	epochO1	0.9934
P1 local tidal phase, in radians from 1-1-1997	epochP1	3.7327
M4 local tidal phase, in radians from 1-1-1997	epochM4	-5.197
Bottom roughness height (m)	z0b	0.012
Minimum bottom friction parameter	cbcmin	0.002
Horizontal diffusion coefficient	HORCON	0.008

4.2 Model Verification

This section compares the model output to oceanographic observations. The primary comparisons are made with a) tidal heights b) main basin seasonal temperature and salinity data, and c) ADCP current meter cross sections.

4.2.1 Tidal Elevation Comparison

Analogous to the tidal calibration, the model was spun up for 30 days, starting 1-1-2000, and the surface elevation predictions were recorded for the following 60 days. A one-week sample of this time series is illustrated in Figure 7, together with the tidal elevation predictions obtained from NOAA and the recorded tidal elevations at the Seattle tide gauge. The model predictions are very similar to the NOAA predictions, which utilize 37 tidal constituents to estimate the tide, instead of the seven included in this model. The recorded observations for this period (March 1 to 7, 2000) are in good agreement with both predictions, although a higher high tide and higher low tide is noticeable during the beginning half of the week.

The M2 and K1 harmonic amplitudes are shown for each tidal station in Figures 8 and 9 (tidal station locations are shown in Figure 5). In both figures, the model appears to overpredict the M2 tidal amplitude by about 5% (6.4 cm), but on average, underpredicts the K1 amplitude by 1.6 cm

(2%). Further adjustment of the open boundary tidal amplitudes would likely improve this bias, however this level of accuracy was deemed acceptable for the purposes of these simulations.

The corresponding M2 and K1 tidal phases are shown in Figures 10 and 11 for each tidal station. A slight bias (1.0 degrees) is evident in the M2 tidal phase, while the K1 phase appears to match the observations fairly well (-0.38 degree bias).

The other 5 tidal harmonics simulated in the model comprise a smaller contribution to the overall tidal signal, and are included in Appendix B

4.2.2 Salinity and Temperature Comparisons

King County maintains a long-term water quality sampling station near the southern end of the Triple Junction, offshore of Point Jefferson (King County, 2001). This data set was used to compare the model's predicted temperature and salinity. Model results for this comparison were output once per day, at midnight local time. The yearly temperature series for 2000, shown in Figure 12, has reasonable agreement. The model's prediction of surface temperature has large day-to-day variations, suggesting that the surface temperature is highly dynamic. In general, the model matches the surface temperature, but the temperature from the 200-m depth appears to lag the observations, and the model under-predicts the summer temperature at depth by about 0.7 ^{o}C.

The model's predicted salinity (Figure 13) at the 200m depth appears similar to the observations for the first nine months, being no more than 0.5 psu above the data. However, the observations show a freshening trend beginning around day 300 that isn't reflected in the model output. The surface salinity has poorer agreement with the observations. The initial model startup condition was too fresh for this location, yet the model did not reflect the large freshening observed around day 130. The model showed a saltier surface layer forming in the summer, but predicted a surface layer that was 0.2 to 1 psu fresher than the observations for the second half of the year.

The comparison with temperature and salinity observations suggest that the model appears to be performing reasonably well overall. However, there are some noticeable discrepancies with the observations. While the Point Jefferson location is close to the outfall zones and likely representative of the model's predictions in the northern Main Basin, the model's predictive ability will vary by location.

4.2.3 Mean Current Comparison

The current observations included deployments of current meters in east-west transects across Puget Sound. Here we compare the model predictions to the observed mean velocity through three transects Edwards Point, Possession Sound, and Point Wells (Figure 2). Details of these measurements, additional cross sectional profiles, and a discussion of factors influencing the circulation pattern are contained in Ebbesmeyer et al. (2002).

The Edwards Point transect used 5 Acoustic Doppler Current Profiler (ADCP) meters along an east-west transect just north of Edwards Point during the period from July to August, 2000. The predicted 29-day mean North-South current speed for July 2000 shows a similar pattern to the observations (Figure 14). A core of northward moving water is seen from 0 to 50 meters on the eastern side of the transect, but located slightly offshore. Southward flowing water is of greatest velocity at depth and along the western slope. In general, the distribution and magnitude of the currents is very similar between the model and observations at this location.

The Possession Sound transect included two ADCP meters and one Aanderaa mooring. The Aanderaa mooring was present for over a year, while the two ADCP meters were placed along this transect from November 2000 to January 2001 and May to June 2001. Only the currents from the earlier deployment are shown in Figure 15. The model's predictions for December 2000 (Figure 15) have some similarities, but the overall pattern appears quite different. Both observations and model predictions suggest a surface layer of outflowing (southward) water, deeper and of greater intensity on the western side of the channel. The current meter observations suggest there is a northward flowing layer of no more than 4 cm/s at mid-depths, concentrated on the western side and practically non-existent in the eastern half of the channel. The model predicts a substantially greater flow focussed along the eastern side, with mean velocities of up to 10 cm/s. Both model and observations suggest a third layer at depth, with the model again suggesting a greater mean flow (12 cm/s) than the observations (about 2 cm/s).

Six ADCP meters and one Aanderaa mooring were deployed in an East-West section off Point Wells from January to March 2001. The observations are reasonably similar to the predicted 29-day mean velocity for February 2001 (Figure 16), with the fastest inflow along the western side of the bottom and the greatest northward velocity near the surface and slightly to the west of the center. The model shows the region with a net northward flow being deeper and extending further east than the observations. The model also has a region of greater northward flow at mid-depths off the eastern shore, which was not seen in the observations. The strong southward flow along the western boundary is also not seen in the observations. Both of these features extend for only a single cell width in the model, suggesting that increased model resolution would be helpful, as well as raising the possibility that the amount of horizontal mixing may need to be increased.

4.3 Uncertainty

In complex models such as the POM model, there are numerous sources of uncertainty and their effect upon the model predictions is difficult to quantify. The cursory comparison with observations described above in model verification, shows the model can predict the observed tidal harmonic amplitudes to within about 5% throughout Puget Sound. On the other hand, the mean circulation, which affects the long-term distribution of tracers, is significantly different from observations in Possession Sound, although reasonably similar to observations within the Main Basin. At Point Jefferson, the year long comparison of salinity and temperature tracers showed general similarity to observations, but appeared to diverge from observations towards the end of the year.

As a result, the model was judged to be adequate to perform short term simulations to model dilution and transport of effluent over several tidal cycles. However, the dissimilarities in mean currents suggested that the model would be inappropriate for long-term simulations of tracer distributions, and the basin-scale model was used to provide estimates of steady-state tracer distributions.

5.0 MODEL SCENARIOS AND RESULTS

The goal of this modeling effort was to provide quantitative results of expected effluent dilution to assist in the evaluation of potential risks. Two scenarios, representing summer and winter seasons, were constructed for each of the three diffuser zones. This chapter describes these scenarios and the results obtained from the model. The use of these dilution estimates in evaluating potential risks can be found in *Phase 3 Brightwater Marine Outfall Water Quality Investigations* (West Consultants and King County, 2002).

Two specific questions were asked of the model: 1) what is the predicted effluent dilution at eleven shoreline locations, and 2) what is the minimum dilution predicted along the bottom of Puget Sound? To provide answers to these questions with a reasonable certainty, the results of the POM model were combined with steady-state predictions from the Basin-Scale model, thus including the short-term plume movement and the long-term circulation throughout Puget Sound.

5.1 Model Scenarios

In order to bracket the effect of seasonal variations on predicted effluent dilution and transport, the months of July 2000 and January 2001 were selected. The summer period generally has greater density stratification in the water column, while a fairly low density stratification is observed during the winter months. These specific months were selected because they coincided with the period of time that both oceanographic measurements were being made within the Triple Junction and density profiles along the model's open boundary were available from JEMS.

For both scenarios, tracer was added to the model cell that corresponded with each outfall zone. The tracer was evenly distributed into the model layers that were within the predicted plume thickness, as determined from the equations given in Roberts et al. (1989). A steady discharge of 3 m^3/s or 68 MGD, through a 500 ft (150 m) diffuser, was assumed in calculating the initial vertical distribution of tracer. Dilutions for other effluent flow rates were obtained by calculating, for each new flow rate, the initial tracer concentration that creates the same mass loading as used within the model. The dilution is found as the ratio of predicted tracer concentration to the initial tracer concentration.

The model was run for a 31-day period, with tracers released from all 3 outfall zones at 5 day intervals and continuing to the end of the model run.

In each scenario, the tracer was started at a specific time and released at a constant, continuous, rate. For each outfall zone, four tracers with staggered start times were used to include a range of atmospheric and tidal conditions. The first set of three tracers, one for each diffuser zone, is released continuously beginning at day 1. The second set of three tracers is released beginning day 6. The third and fourth sets are released on days 11 and 16, respectively.

The tracer concentration at each of the 11 shoreline sites was recorded at half-hour intervals for the duration of the 31-day model run. To compute the mean dilution, the daily average concentration of each tracer on the tenth day following its initial release (days 11,16,21 and 26) was first calculated. Then the four tracers were averaged together to arrive at a mean concentration. The minimum dilution reported corresponds to the lowest dilution observed from any of the four tracers, at any time within the first ten days following their initial release. This provided an estimate of the dilution associated with short-term plume movement, and was combined with the steady-state dilution estimate obtained from the Basin-scale model to provide the final dilution estimate.

Estimates of the minimum near-bottom dilution were obtained by recording the maximum concentration within the deepest model layer on the thirtieth day of the simulation run. This yielded results at 15, 20, 25, and 30 days after release for the four tracers. These results were fit to a first order decay equation to separate this into components due to the initial plume movement and due to the long-term buildup of effluent in the region. The component attributed to the initial plume movement was then combined with the steady-state dilution estimate from the Basin Scale model to estimate the minimum near-bottom dilution.

5.2 Basin Scale Model

All three outfall zones are located within the Main Basin box of the Basin Scale model. The effluent was entered into the bottom layer, consistent with the plume trapping at depths below 50m. This model also required input as a mass loading rate, so the initial concentration was scaled according to the effluent flow to equate to the mass loading entered into the model. The model predicted steady-state concentrations within each box, from which dilutions were calculated. The predicted dilutions are summarized in Table 3. To match the effluent flows used in the POM model, the maximum monthly flows were also used with the Basin Scale model. The annual average flowrate would be more consistent with the annual-averaged concentrations predicted by this model, implying that the dilutions listed in Table 3 are conservative (too small) by about 25%.

Table 3.
Annual average dilutions in the Main Basin predicted from the Basin Scale model

Plant Capacity (AWWF)	Effluent Flow Rate (Max Monthly Flow)	Steady-State Dilution (upper layer)	Steady-State Dilution (lower layer)
36 MGD	45 MGD	4440	4340
54 MGD	68 MGD	2960	2890
72 MGD	90 MGD	2220	2170

5.3 Summer Scenario Results

The summer scenario provided dilution results for both the shoreline locations and the near-bottom.

5.3.1 Shoreline Results

The model recorded tracer concentrations at half-hour intervals at the 11 shoreline locations, from which the mean and maximum concentrations were calculated. The daily average dilution was computed by averaging the model concentrations at half hour intervals over the 24-hour period comprising the tenth day after release. The results presented below are either the average or minimum of four tracers, each after 10 days of continuous release, with staggered starting times on days 1, 6, 11, and 16 of the month. The maximum concentration that occurred between the tracer start and the end of the tenth day was used to compute the minimum dilution.

The concentrations were normalized by the initial tracer concentration to produce the equivalent dilution, and are summarized in Table 4. These dilutions are very large, greater than 8000:1, implying that the plume is not advected directly towards the surface but remains trapped at depth. The locations with the lowest dilutions were Pt. Wells, Richmond Beach and Carkeek Park. These sites are near or immediately south of the outfall zones. Sites further from the outfall zones tended to have greater dilution. The minimum dilutions for each flow rate were 16661:1 (45 MGD), 11107:1 (68 MGD), and 8331:1 (90 MGD). Note that the discharge from a 72 MGD treatment plant was not included for Zone 7S, as that option is not being evaluated.

For each outfall zone and discharge rate, the minimum dilution is combined with the annual average dilution (Equation 1) from the Basin Scale model in Table 5. The long-term average dilution represents the majority of the total dilution estimate.

$$\text{minimum dilution} = \frac{1}{\dfrac{1}{\text{min POM dilution}} + \dfrac{1}{\text{annual average dilution}}} \qquad (1)$$

The model was run with a discharge rate of $3 m^3/s$ (68MGD) and dilutions corresponding to flow rates of $2.25\ m^3/s$ (45 MGD) and $4.5\ m^3/s$ (90 MGD) were calculated by adjusting the initial tracer concentration to match the mass loading rate.

Table 4.
Near-surface Dilutions Under Summer Conditions – July 2000

10 Days after start of release Average of four releases	Daily Average Dilution (45 MGD discharge)			Daily Average Dilution (68 MGD discharge)			Daily Average Dilution (90 MGD discharge)	
Shoreline Landmark	**Zone 6**	**Zone 7N**	**Zone 7S**	**Zone 6**	**Zone 7N**	**Zone 7S**	**Zone 6**	**Zone 7N**
Mukilteo State Park	124379	219408	252525	82919	146272	168350	62189	109704
Naketa Beach	111840	188834	214300	74560	125889	142867	55920	94417
Picnic Point	83232	117353	127173	55488	78235	84782	41616	58676
Meadowdale Park	68682	83598	87428	45788	55732	58285	34341	41799
Edmonds Beach	64505	41799	40454	43003	27866	26969	32253	20900
Pt Wells	57107	36411	35514	38071	24274	23676	28553	18206
Richmond Beach	54324	34163	33417	36216	22775	22278	27162	17082
Carkeek	54665	34587	33546	36443	23058	22364	27332	17293
Golden Gardens	72255	45905	44160	48170	30603	29440	36127	22952
Fay-Bainbridge State Park	101537	62874	58050	67691	41916	38700	50768	31437
Kingston Cove	65735	67988	67794	43823	45325	45196	32867	33994
	Minimum Dilution			**Minimum Dilution**			**Minimum Dilution**	
Mukilteo State Park	71232	117023	129344	47488	78015	86229	35616	58511
Naketa Beach	58863	86226	96377	39242	57484	64251	29431	43113
Picnic Point	50934	53135	54611	33956	35423	36407	25467	26567
Meadowdale Park	46589	45722	45300	31059	30481	30200	23294	22861
Edmonds Beach	40287	25533	25533	26858	17022	17022	20143	12766
Pt Wells	29343	18977	18977	19562	12651	12651	14672	9489
Richmond Beach	**24699**	**16661**	18003	**16466**	**11107**	12002	**12349**	**8331**
Carkeek	26933	17430	**17096**	17955	11620	**11397**	13466	8715
Golden Gardens	33210	21369	20739	22140	14246	13826	16605	10685
Fay-Bainbridge State Park	59576	37808	34736	39717	25205	23157	29788	18904
Kingston Cove	47720	38250	37095	31813	25500	24730	23860	19125

Table 5.
Minimum Predicted Shoreline Dilutions Combining Minimum Summer Scenario Shoreline Dilution From POM Model with Steady-State Dilution from the Basin Scale Model

Plant Capacity (AWWF)	Effluent Flow Rate (Max Monthly Flow)	Steady-State Dilution (upper layer)	Minimum Nearshore Dilution (10 day release)	Minimum Nearshore Dilution (combined)
Zone 6 - 36 MGD	45 MGD	4440	24699	3760
Zone 7N - 36 MGD	45 MGD	4440	16661	3510
Zone 7S - 36 MGD	45 MGD	4440	17096	3520
Zone 6 - 54 MGD	68 MGD	2960	16466	2510
Zone 7N - 54 MGD	68 MGD	2960	11107	2340
Zone 7S - 54 MGD	68 MGD	2960	11397	2350
Zone 6 - 72 MGD	90 MGD	2220	12349	1880
Zone 7N - 72 MGD	90 MGD	2220	8331	1750

5.3.2 Near Bottom Results

Table 6.
Near Bottom Dilutions After Various Release Durations (Summer scenario)

Day after release start	Minimum Near-bottom Dilution (68 MGD Discharge)			Minimum Near-bottom Dilution (90 MGD Discharge)	
5 days	863	618	703	648	463
10 days	844	608	688	633	456
15 days	830	601	679	622	451
20 days	817	594	671	613	446
25 days	806	589	665	605	442
30 days	797	584	659	598	438

The minimum near-bottom concentrations are given in Table 6 from the recorded half-hour concentration values in the lowest model layer in all model cells. To estimate the minimum near-bottom dilution under steady state conditions, the model results were regressed with a simple equation. This equation describes the time varying concentration created by the mixing of a source (constant concentration) with an ambient (background) concentration that increases in time towards a steady-state value. This equation is given by:

$$C = Cm - Ca*\exp(-t/T) \qquad (2)$$

where Cm and Ca are constants so that the steady state concentration reach is Cm and the initial concentration is (Cm-Ca), with t representing time and T the characteristic time for background concentration accumulation. These concentrations can be converted the equivalent dilution (S) by:

$$S = C0/C \qquad (3)$$

where C0 is the initial tracer concentration. Equations (2) and (3) can be combined to give:

$$1/S = 1/Sm - (1/Sa)*\exp(-t/T) \quad (4)$$

where C/C0= 1/S, Cm/C0 = 1/Sm, and Ca/C0 = 1/Sa. Sm represents the steady-state minimum dilution, and Sa the contribution of the background concentration. From this equation, the minimum near-bottom dilution that would occur once the system reached a steady-state can be estimated in two ways. The minimum dilution can be taken directly as Sm, or the near-diffuser concentration (Cm-Ca) can be combined with the predicted background contribution obtained from the Basin-Scale model (Table 3) to estimate the dilution. The results from these two methods agree to within 10% of each other, with the second method resulting in lower dilutions. These values are given in Table 7. The minimum dilution is predicted to be 387:1 with a discharge rate of 90 MGD.

Table 7.
Minimum Predicted Near-Bottom Dilutions Combining Minimum Summer Scenario Near-Bottom Dilution from POM Model with Basin-Scale Model.

Simulation	Zone	Flow Rate (Maximum Monthly Flow)	Near-Bottom Dilution (So=1/(Cm-Ca)) from Eqn (1)	Basin-Scale model ambient Dilution (Sb)	Combined Dilution Prediction of (Cm-Ca) + 1/Sb
Summer	6	45 MGD	1325	4337	1015
	7N	45 MGD	942	4337	774
	7S	45 MGD	1074	4337	861
	6	68 MGD	883	2870	675
	7N	68 MGD	628	2870	515
	7S	68 MGD	716	2870	573
	6	90 MGD	662	2169	507
	7N	90 MGD	471	2169	387

5.4 Winter Scenario Results

The results of the winter scenario are very similar to those of the summer scenario. The results are presented in an identical format, with the shoreline dilutions presented in Tables 8 and 9 and the near-bottom dilutions in Tables 10 and 11. Again, the shoreline dilutions were found as the average or minimum of four tracers, each after 10 days of continuous release, recorded at half-hour intervals.

The model was run with a discharge rate of 3 m^3/s (68MGD) and dilutions corresponding to flow rates of 2.25 m^3/s (45 MGD) and 4.5 m^3/s (90 MGD) were calculated by adjusting the initial tracer concentration to match the mass loading rate.

A greater variation in dilutions between winter and summer may be expected based on the typical seasonal cycle of density stratification within Puget Sound. However, the model over-predicted the density stratification during the winter scenario period (Figure 13), resulting in conditions more typical of summer. The effect of this is hard to quantify without additional investigation.

As with to the shoreline dilutions, the near-bottom dilution estimates are similar to the summer scenarios, with a minimum dilution of 346:1. This is slightly lower than the minimum summer dilution of 387:1.

Table 8.
Near-surface dilutions under winter conditions – Winter Scenario

10 Days after start of release Average of four releases	Daily Average Dilution (45 MGD discharge)			Daily Average Dilution (68 MGD discharge)			Daily Average Dilution (90 MGD discharge)	
Shoreline Landmark	**Zone 6**	**Zone 7N**	**Zone 7S**	**Zone 6**	**Zone 7N**	**Zone 7S**	**Zone 6**	**Zone 7N**
Mukilteo State Park	83259	142207	166876	55506	94805	111251	41630	71104
Naketa Beach	68453	109497	126796	45635	72998	84531	34226	54749
Picnic Point	53575	76472	86351	35717	50981	57567	26788	38236
Meadowdale Park	44549	59735	66135	29699	39823	44090	22274	29867
Edmonds Beach	57899	40220	38233	38600	26813	25489	28950	20110
Pt Wells	58434	36673	34879	38956	24449	23253	29217	18337
Richmond Beach	52931	31262	29933	35287	20841	19955	26465	15631
Carkeek	48406	26778	25332	32271	17852	16888	24203	13389
Golden Gardens	52120	29562	28089	34746	19708	18726	26060	14781
Fay-Bainbridge State Park	101208	52787	48603	67472	35191	32402	50604	26394
Kingston Cove	58252	55060	53910	38835	36707	35940	29126	27530
	Minimum Dilution			**Minimum Dilution**			**Minimum Dilution**	
Mukilteo State Park	43115	73910	86227	28743	49273	57484	21557	36955
Naketa Beach	31406	49899	58863	20938	33266	39242	15703	24949
Picnic Point	32125	42372	47952	21416	28248	31968	16062	21186
Meadowdale Park	30913	37955	39321	20608	25303	26214	15456	18977
Edmonds Beach	29520	23076	21005	19680	15384	14003	14760	11538
Pt Wells	34251	18904	19351	22834	12603	12900	17126	9452
Richmond Beach	33665	18306	18760	22443	12204	12507	16832	9153
Carkeek	32987	**18070**	**17808**	21991	**12047**	**11872**	16493	**9035**
Golden Gardens	**31916**	18940	18070	**21277**	12627	12047	**15958**	9470
Fay-Bainbridge State Park	43496	21796	21095	28997	14531	14063	21748	10898
Kingston Cove	41831	38550	37520	27887	25700	25013	20915	19275

Table 9.
Minimum Predicted Shoreline Dilutions Combining Minimum Winter Scenario Shoreline Dilution from POM Model With Steady-State Dilution from the Basin Scale Model

Plant Capacity (AWWF)	Effluent Flow Rate (Max Monthly Flow)	Steady-State Dilution (upper layer)	Minimum Nearshore Dilution (10 day release)	Minimum Nearshore Dilution (combined)
Zone 6 - 36 MGD	45 MGD	4440	29500	3860
Zone 7N - 36 MGD	45 MGD	4440	18100	3560
Zone 7S - 36 MGD	45 MGD	4440	17800	3550
Zone 6 - 54 MGD	68 MGD	2960	19700	2570
Zone 7N - 54 MGD	68 MGD	2960	12000	2380
Zone 7S - 54 MGD	68 MGD	2960	11900	2370
Zone 6 - 72 MGD	90 MGD	2220	14800	1930
Zone 7N - 72 MGD	90 MGD	2220	9040	1780

Table 10.
Near bottom dilutions after various release durations (Winter scenario)

Day after release start	Minimum Near-bottom Dilution (68 MGD Discharge)			Minimum Near-bottom Dilution (90 MGD Discharge)	
5 days					
10 days					
15 days	691	508	564	519	381
20 days	681	501	554	511	375
25 days	673	494	546	504	371
30 days	665	489	539	499	367

Table 11.
Minimum Predicted Near-Bottom Dilutions Combining Minimum Winter Scenario Near-Bottom Dilution from POM Model with Steady-State Dilution from The Basin Scale Model

Simulation	Zone	Flow Rate (Maximum Monthly Flow)	Near-Bottom Dilution (So=1/(Cm-Ca)) from Eqn (1)	Basin-Scale model ambient Dilution (Sb)	Combined Dilution Prediction of (Cm-Ca) + 1/Sb
Winter	6	45 MGD	1103	4337	879
	7N	45 MGD	822	4337	691
	7S	45 MGD	920	4337	759
	6	68 MGD	735	2870	585
	7N	68 MGD	548	2870	460
	7S	68 MGD	613	2870	505
	6	90 MGD	551	2169	440
	7N	90 MGD	411	2169	346

5.5 Dilution Comparison to other Models

This section compares a few aspects of the simulation results to results available from other models to verify that the results are, in fact, reasonable. The long-term dilution estimate that was separated from the near-bottom dilutions estimates ranged from 2941:1 to 4545:1 (Table 12). These results are 2% to 58% higher than the Basin Scale model predictions. Thus the Basin Scale model predicts a higher steady-state concentration, which is as expected. The long-term dilution estimate from the POM model is based on a 30-day run, in which tracer is distributed over much of the Main Basin, but little reaches the further basins (South Sound, Whidbey Basin, Hood Canal) of Puget Sound. Refluxing of water from these basins would be expected to further lower the dilution estimate. However, these results appear to indicate that the two models are in reasonable agreement on the magnitude of dilution that can be expected basin wide.

Table 12.
Comparison of steady state dilutions for bottom layer of Main Basin

Scenario Description	Steady-state estimate from extrapolation of POM and equation (3)	Basin Scale Model
Summer, Zone 6, 68 MGD	4545	2890
Summer, Zone 7N, 68 MGD	4545	2890
Summer, Zone 7S, 68 MGD	4545	2890
Winter, Zone 6, 68 MGD	3846	2890
Winter, Zone 7N, 68 MGD	2941	2890
Winter, Zone 7S, 68 MGD	2941	2890

Comparison of the POM results with the PLUMES model results is hampered by two factors. The POM model cell, at 600m x 900m, is much larger than the zone of initial dilution, typically 150m x 50-300m (for a 500-ft diffuser). Secondly, the PLUMES predictions are for the minimum dilution in the vertical water column, while the POM results were summarized for the lower layer, usually below the plume’s trapping depth. The ambient density profiles used in the PLUMES model were selected to represent more extreme conditions than included in the POM model. Depending on ambient current speed, the PLUMES model predicted minimum dilutions for a 68 MGD discharge, at the edge of the hydrodynamic mixing zone, to be in the range of 206-776 for summer conditions, and 476-1403 under winter conditions. For comparison, the minimum near bottom dilutions from the POM model ranged from 515-675 in summer, and 460-585 in winter. These values are of the same order as the PLUMES model results, suggesting that these results are reasonable. The results also appear to indicate that the reduction in dilution from previous effluent mixing with the current discharge is not excessive. The dilution estimates of the PLUMES and the POM near-bottom results are located at different vertical depths and incorporate different density stratification, making a more detailed comparison of these results difficult.

5.6 Conclusions

The shoreline dilution values, greater than 8,000:1, indicate that the model does not advect the tracer plume from its release depth to the surface. Estimates of effluent dilution at the shoreline locations are dominated by the annual-average estimate obtained from the Basin Scale model. Including the annual average dilution, the minimum shoreline dilution was 8331:1

Near-bottom dilutions were greater than 340:1 in all scenarios. This includes refluxing of the plume and the annual-average dilution from the Basin-Scale model. This is a reasonably high dilution value, indicating that the outfall zones receive good mixing with the ambient waters.

The winter scenario results appear similar to the summer scenario, potentially due to an over-prediction of density stratification during the winter months by the POM model. The impact of this over-prediction, as well as the impact of other modeling uncertainties, is difficult to evaluate. The results of the PLUMES modeling indicate that the discharge would remain submerged under the winter discharge conditions. Therefore, large changes in the shoreline dilution are not expected.

6.0 SUMMARY

The circulation model of Puget Sound was based on the Princeton Ocean Model (POM), a primitive equation ocean model, which has an extensive history of use for modeling of estuaries, coastal regions, and open oceans. The model included all of Puget Sound at a 600 m by 900 m grid resolution, and extended into the Strait of Juan de Fuca as far as the southern tip of Vancouver Island. A number of modifications were made to the model, including the addition of atmospheric coupling, river inflows, and an advanced advection algorithm, to simulate processes important within Puget Sound.

The model was used to predict effluent dispersion and dilution under a summer and winter scenario for each potential diffuser zone. The model simulated an effluent discharge from the bottom of Puget Sound and traced the effluent for a 10-day period. These results were combined with a separate calculation of the long-term dilution to estimate the potential additional contribution of the proposed outfall toward the concentration of conservative substances within Puget Sound.

The model predicted that the discharged effluent would be trapped at depth, and very low concentrations would reach shoreline locations within 10 days. Including the long-term accumulation of effluent in Puget Sound, dilutions of no less than 1750:1 were predicted. The dilution near the seafloor, where the effluent plume reaches the bottom, was predicted at more than 340:1. These predictions show that the proposed discharges have very high dilutions and are unlikely to reach shoreline sites without significant additional mixing.

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Figures

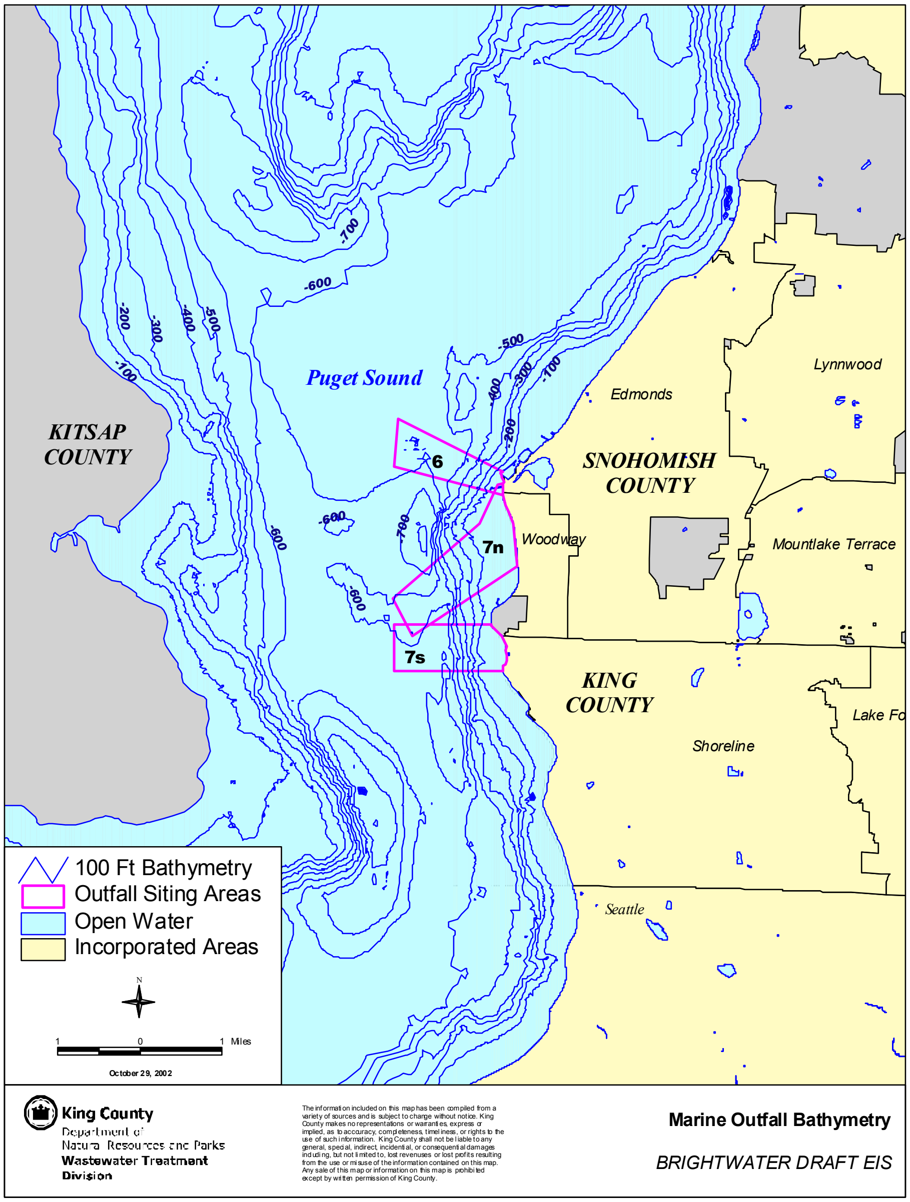


Figure 1. Puget Sound Bathymetry and Locations of the Three Alternative Outfall Zones.

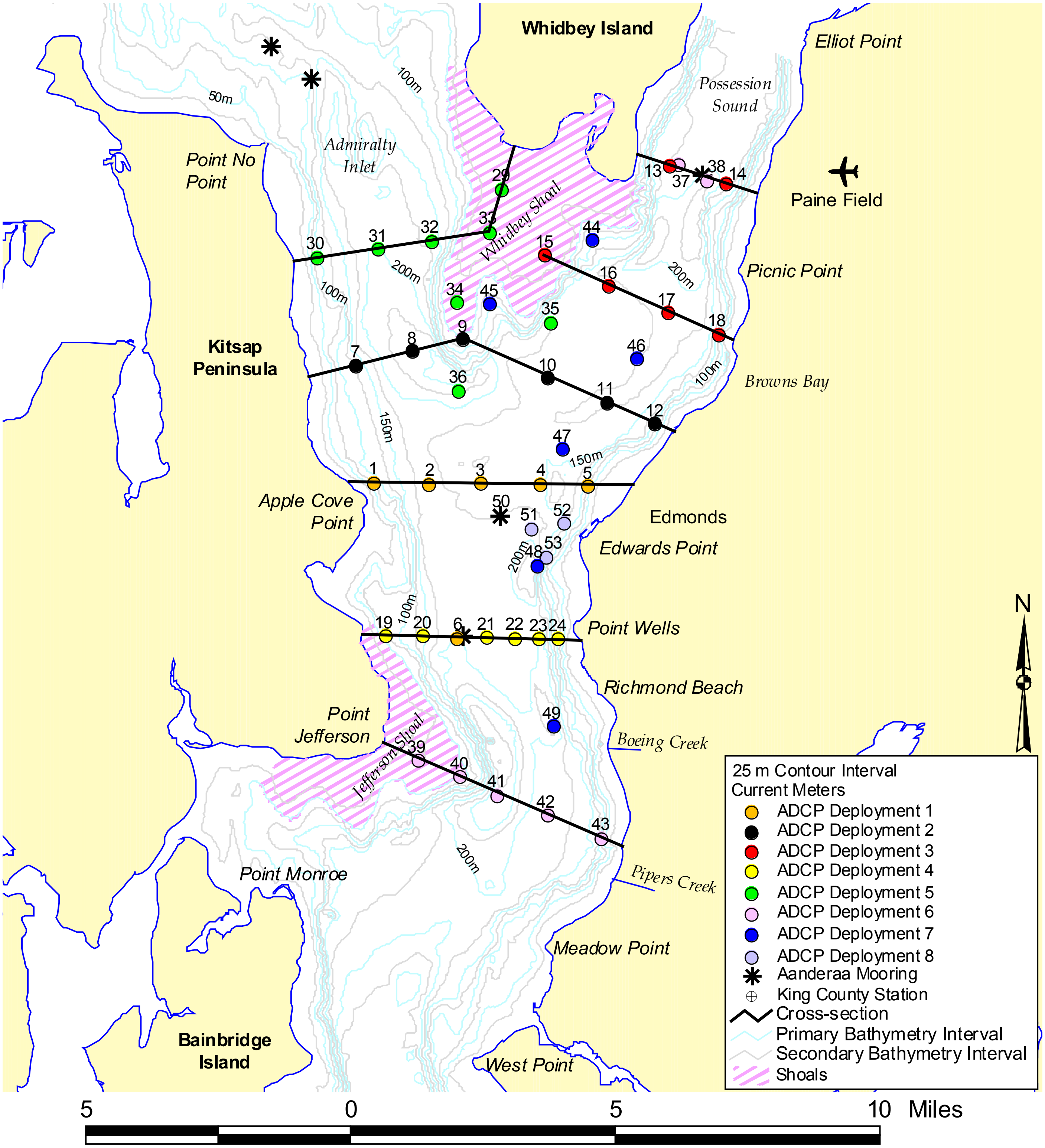


Figure 2. Locations of current meter deployments (from: Ebbesmeyer et al, 2002)

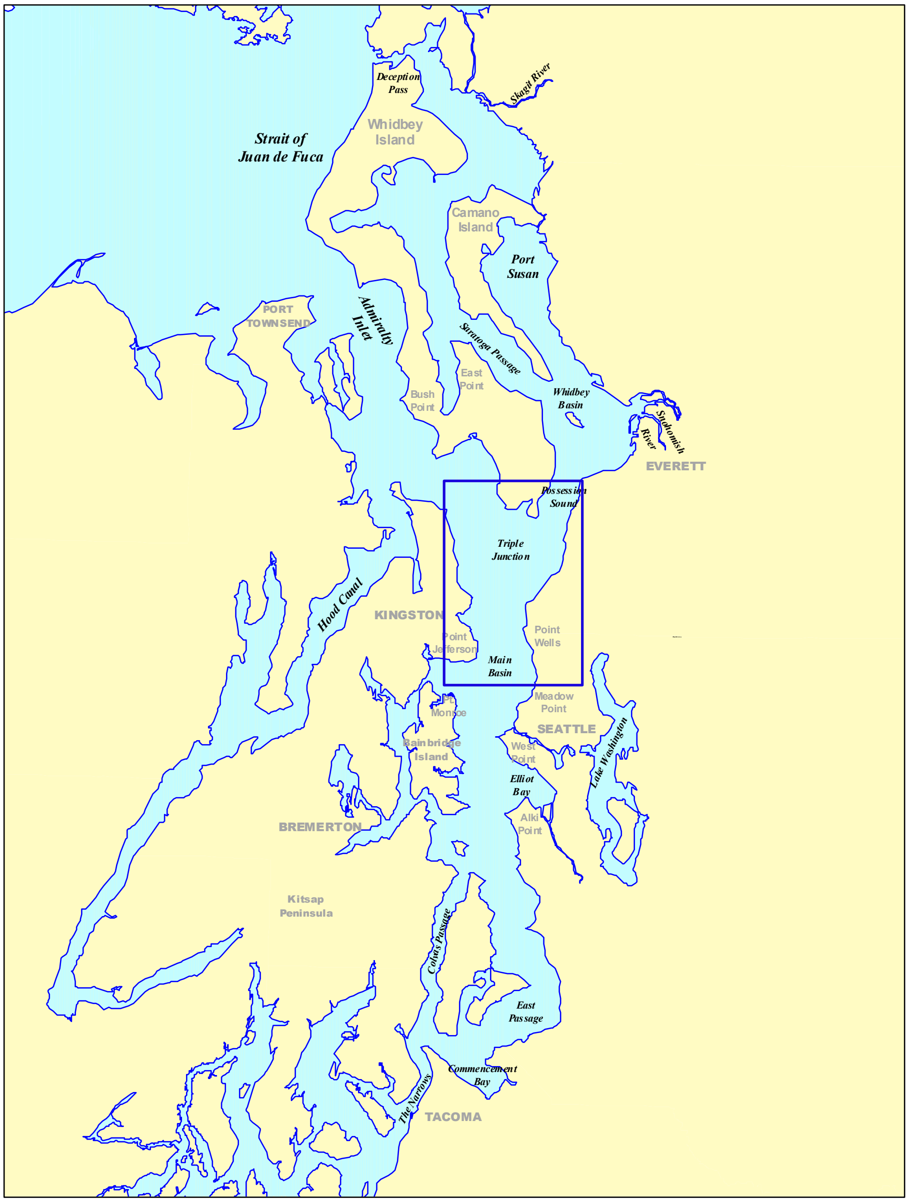


Figure 3. Puget Sound. The Triple Junction Region is enclosed in the boxed area.

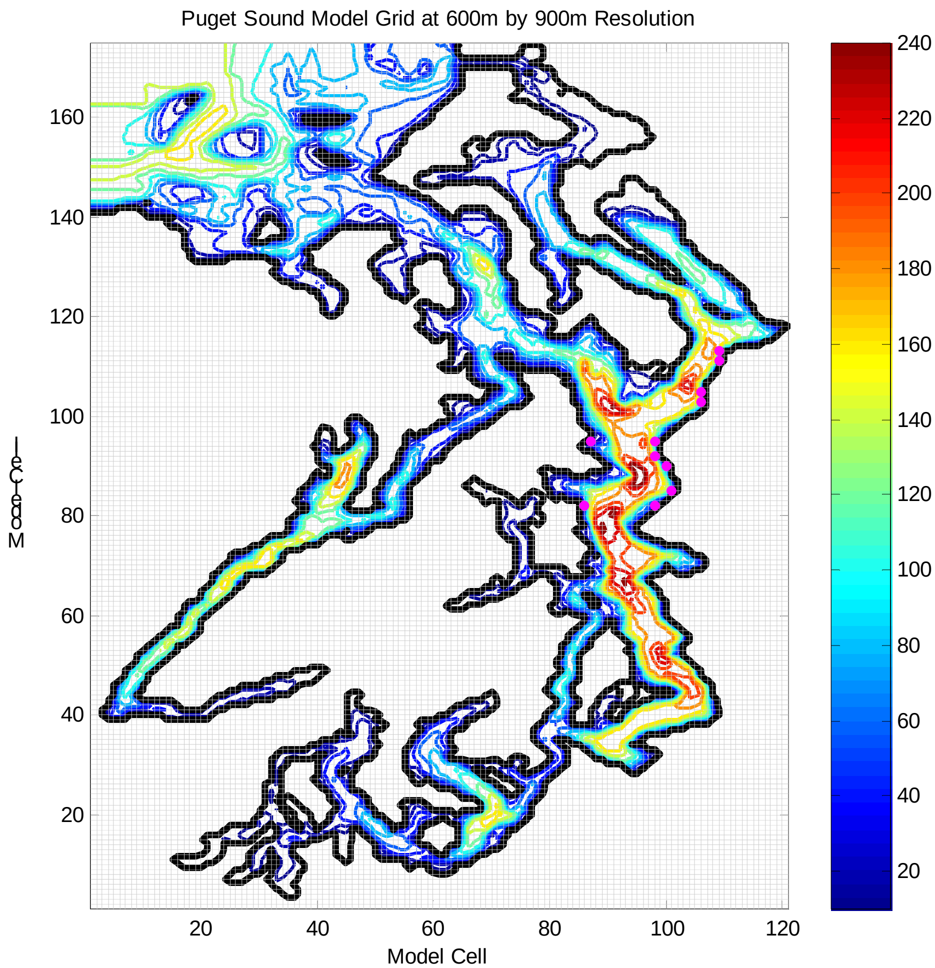


Figure 4. Model grid of uniform 600 m x 900 m cells used for Puget Sound (POM) model. The colored contour lines indicate the depth in meters. Pink dots indicate the grid cells of the 11 shoreline use areas.

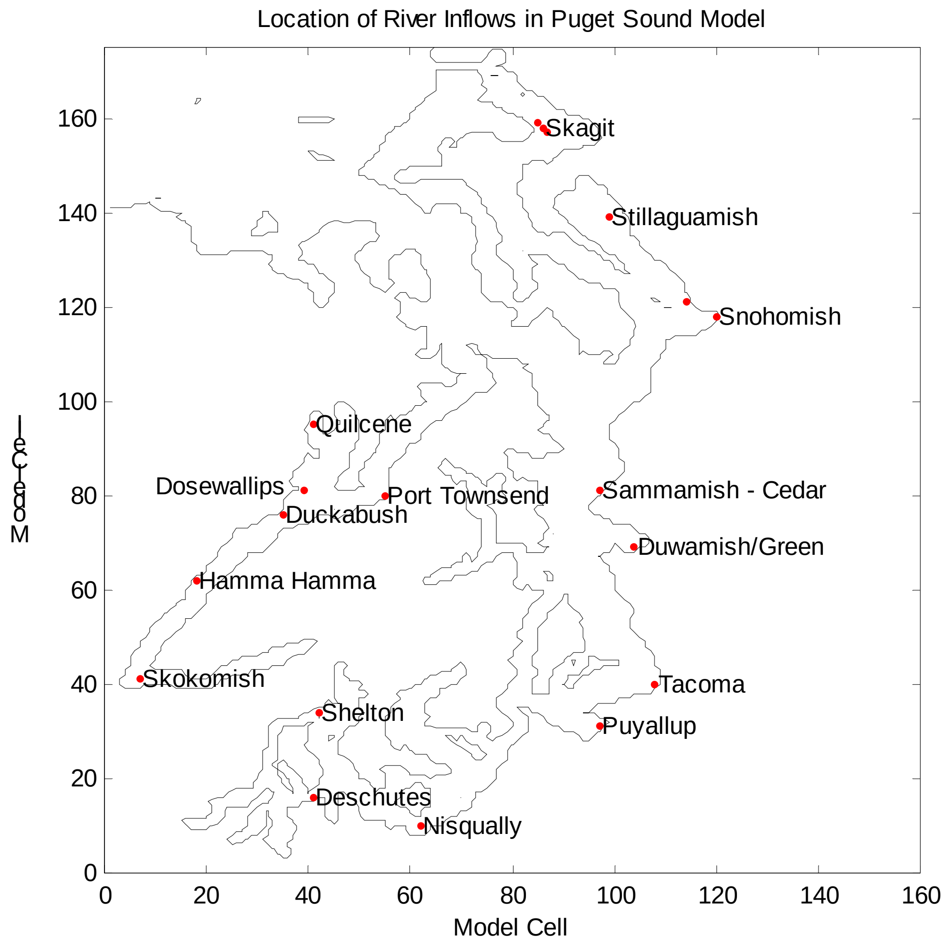


Figure 5. Location of fresh-water inputs into Puget Sound model.

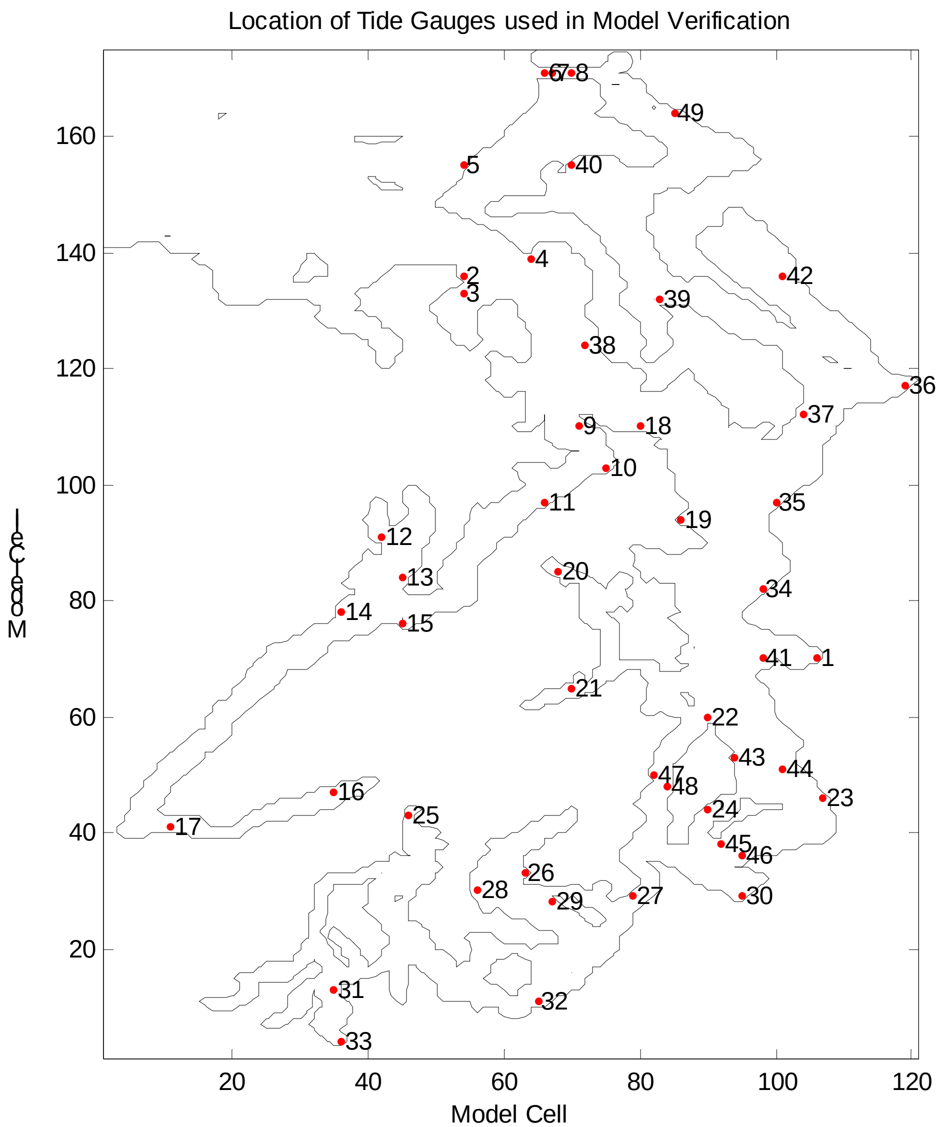


Figure 6. Locations of tidal stations used to calibrate and verify Puget Sound model.

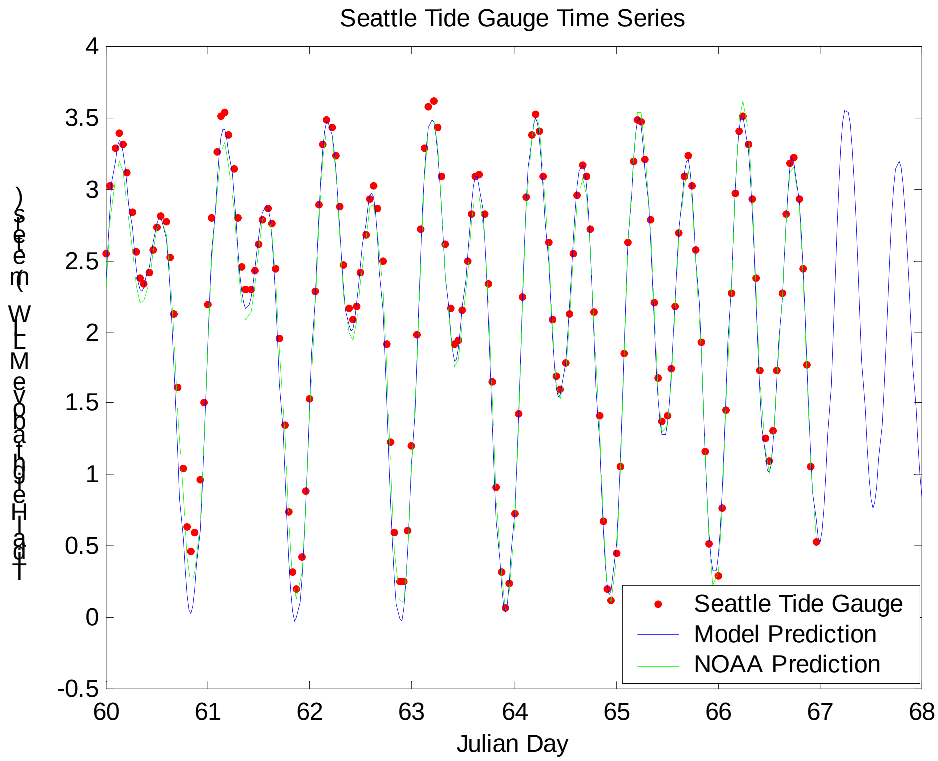


Figure 7. Sample time series comparison between Puget Sound model predictions (blue line), NOAA 37-harmonic prediction (dashed green line), and Seattle tide gauge records (red dots) for a one week period in 2000.

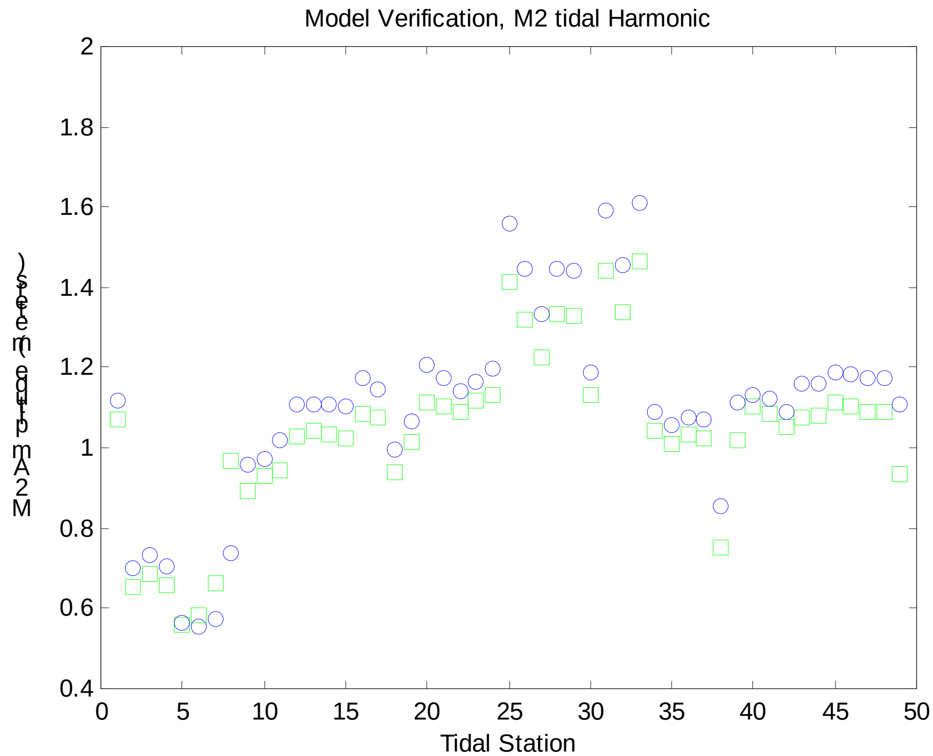


Figure 8. Observed (squares) and modeled (circles) harmonic amplitude of the M2 tide at tidal stations throughout Puget Sound.

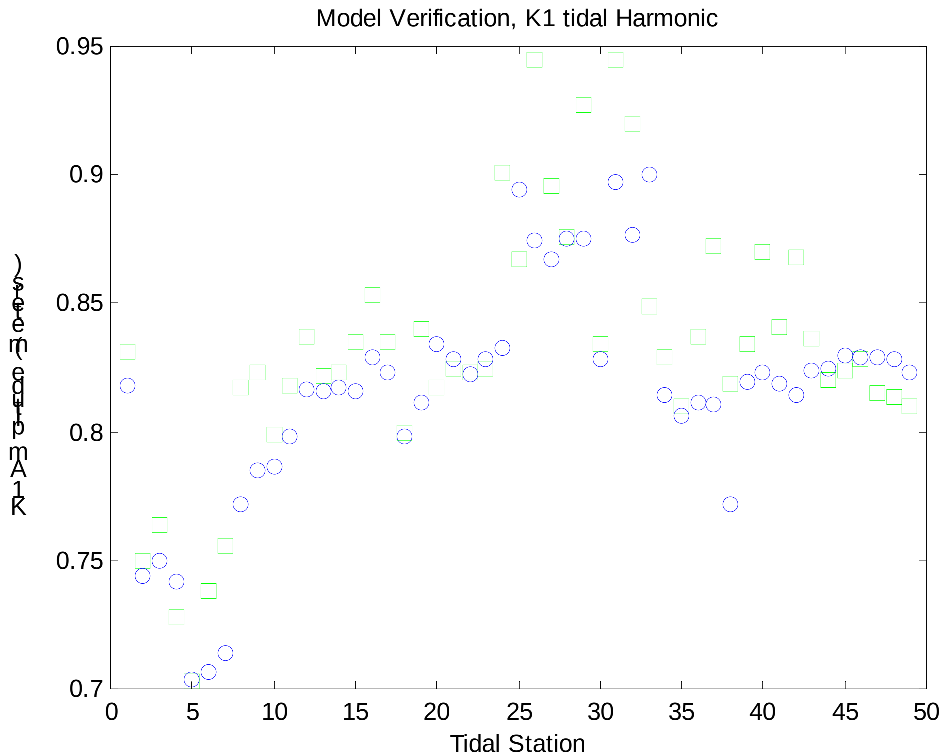


Figure 9. Observed (squares) and modeled (circles) harmonic amplitude of the K1 tide at tidal stations throughout Puget Sound.

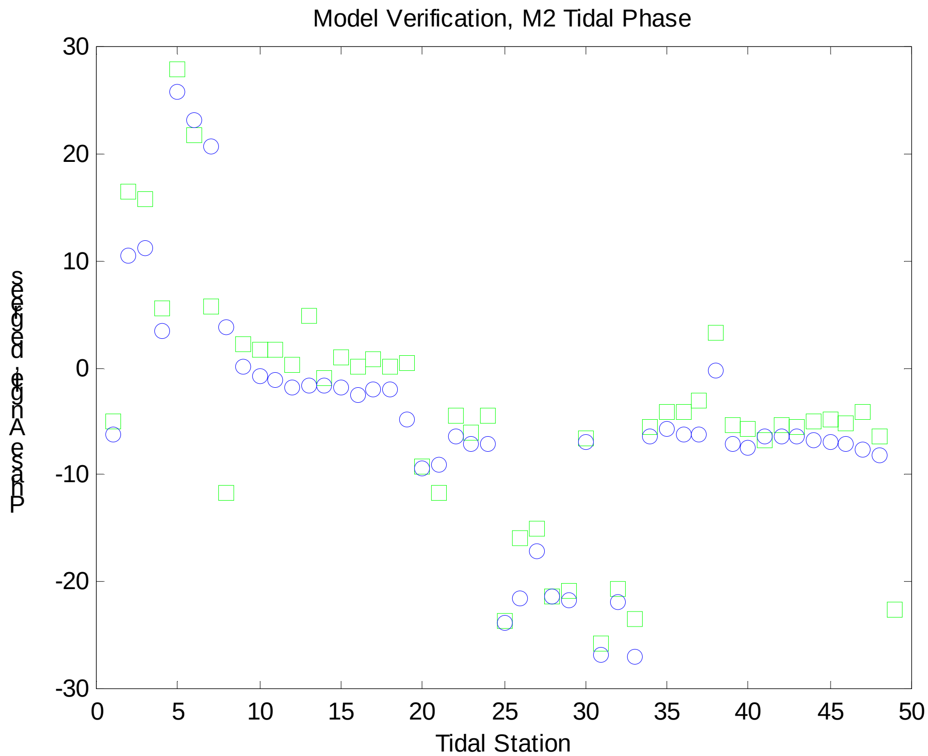


Figure 10. Observed (squares) and modeled (circles) tidal phases of the M2 tide at tidal stations throughout Puget Sound.

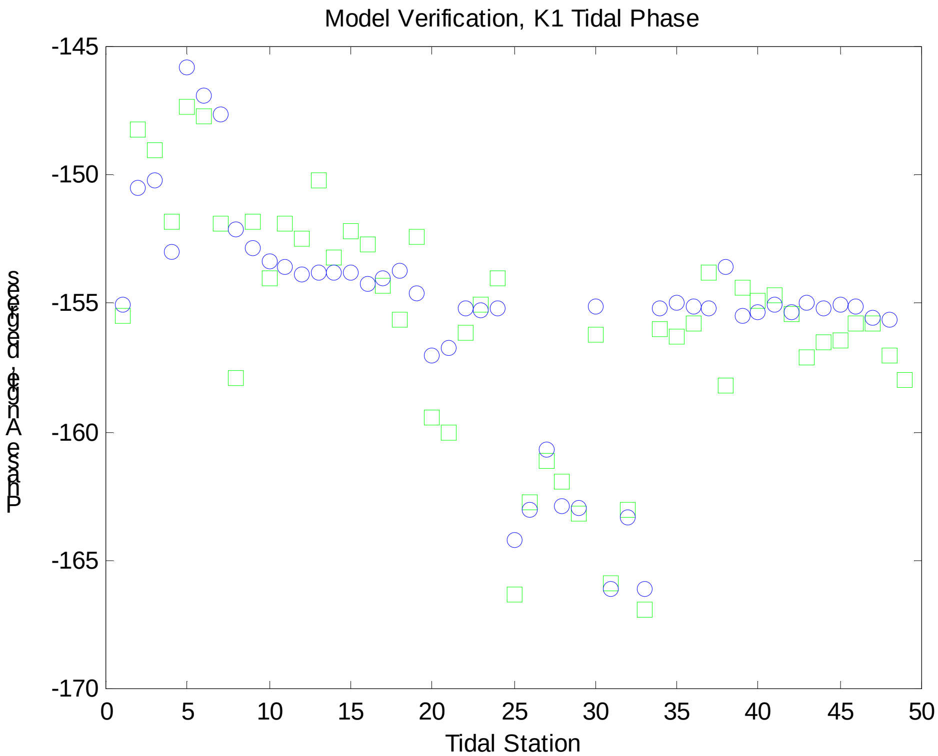


Figure 11. Observed (squares) and modeled (circles) tidal phases of the K1 tide at tidal stations throughout Puget Sound.

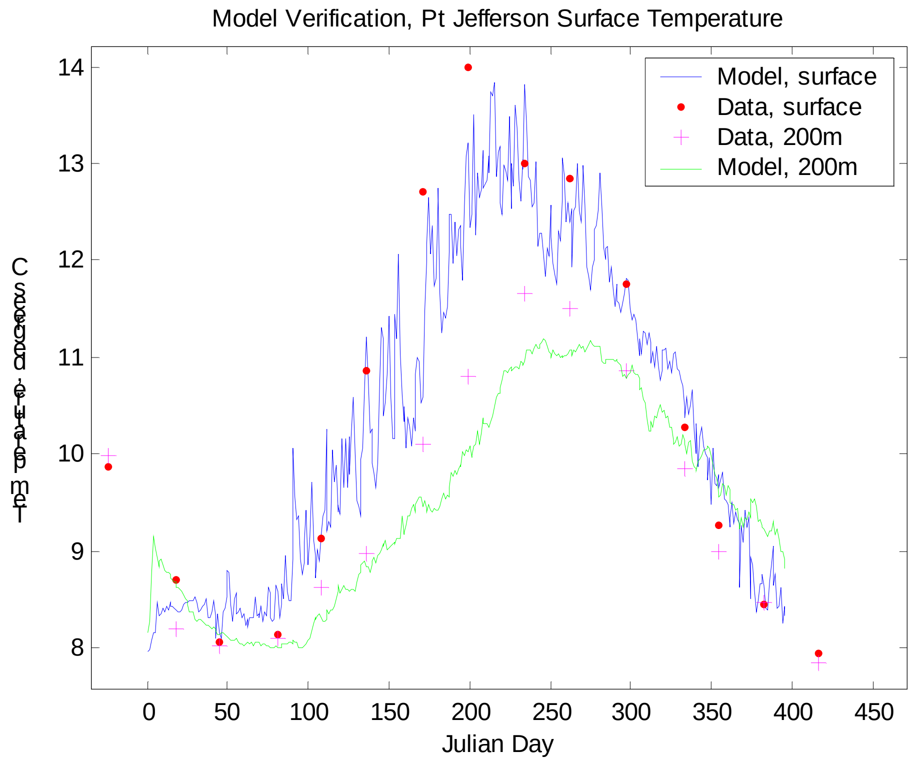


Figure 12. Observations (dots, crosses) and model predictions (lines) for surface and bottom temperatures at the Point Jefferson (KSBP01) sampling station.

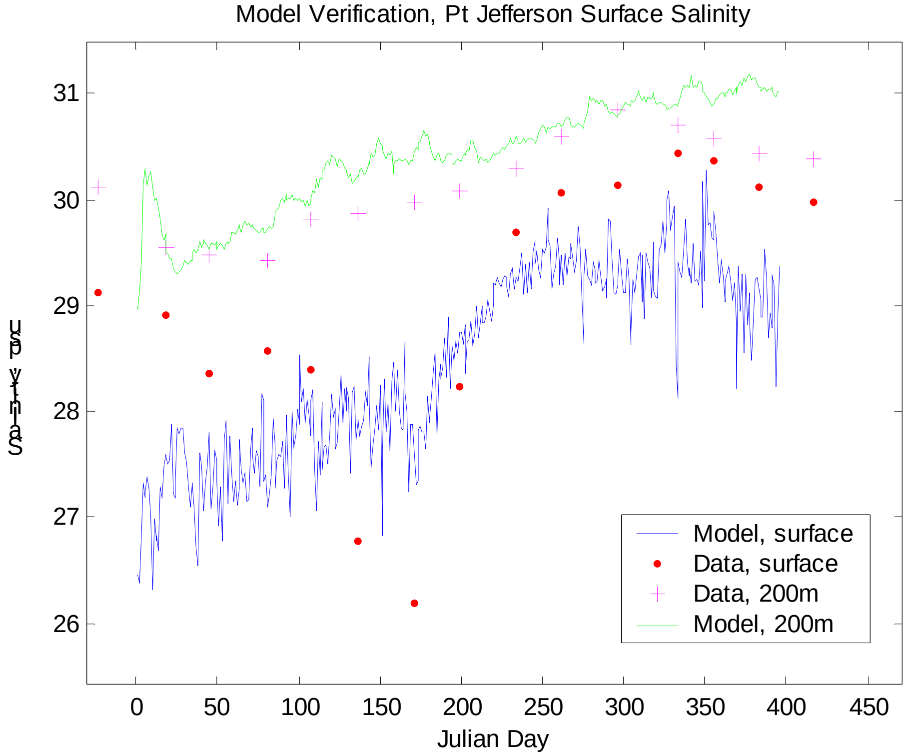


Figure 13. Observations (dots, crosses) and model predictions (lines) for surface and bottom salinity at the Point Jefferson (KSBP01) sampling station.

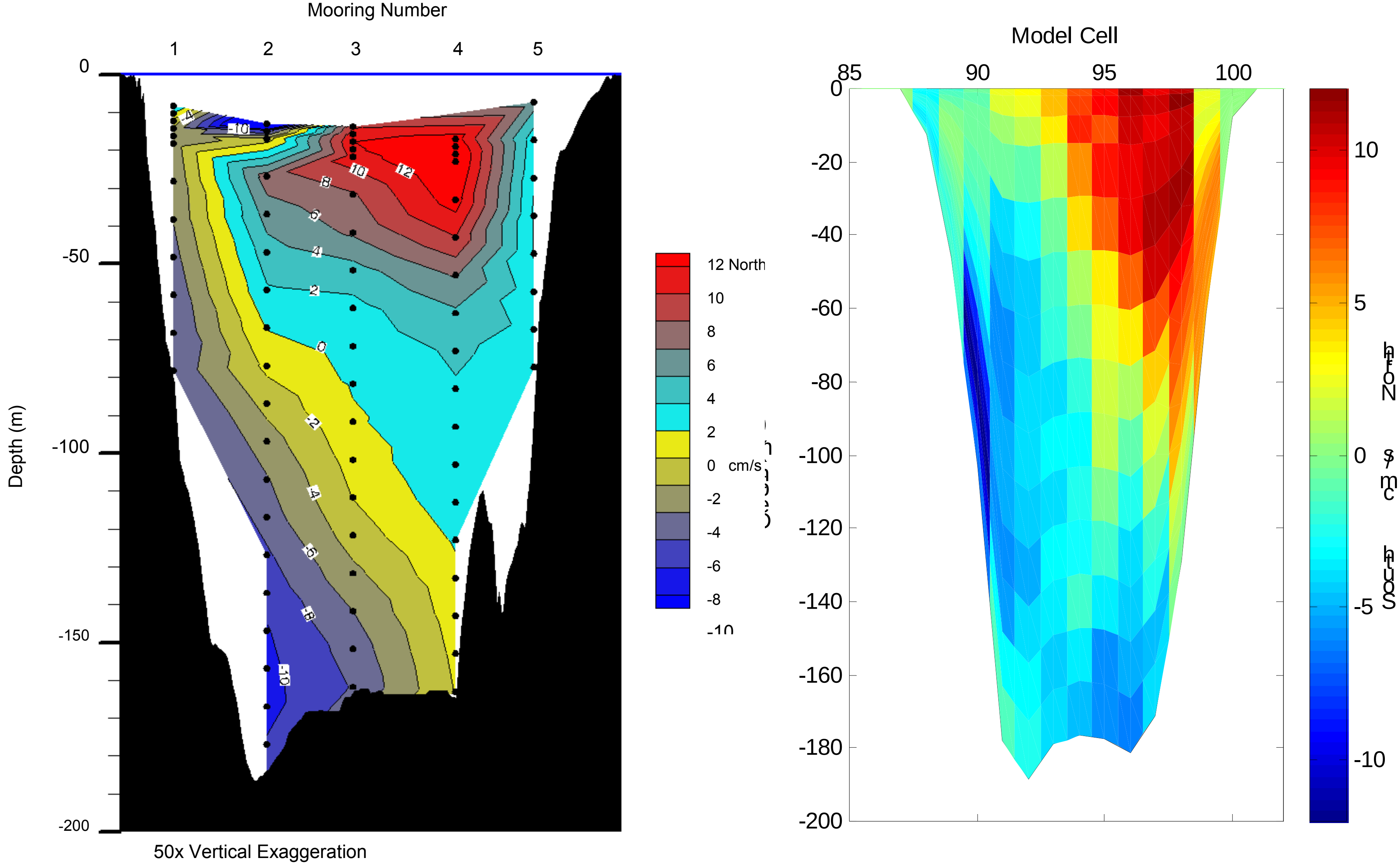


Figure 14. Mean current speeds perpendicular to Edwards Point Transect (July 14-August 10, 2000; from Ebbesmeyer et al., 2002) and model predictions of mean north-south current speeds (m/s) at the same location (model cell j = 97; June 28-July27, 2000)

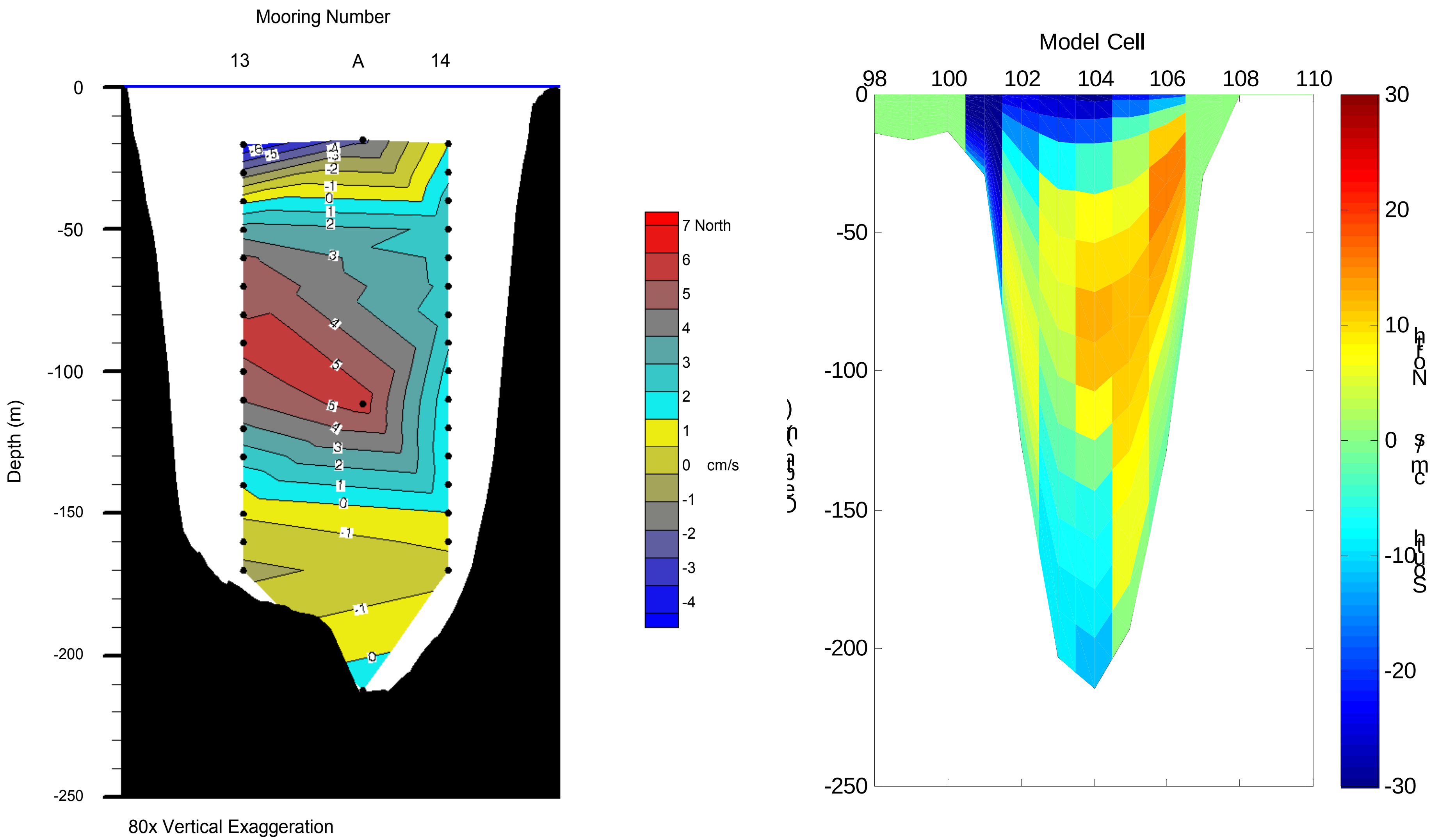


Figure 15. Mean current speeds perpendicular to Possession Sound transect (December 1-28, 2000; from Ebbesmeyer et al., 2002) and model predictions of mean north-south current speeds (m/s) at the same location (model cell j = 108; November 25-December 24, 2000).

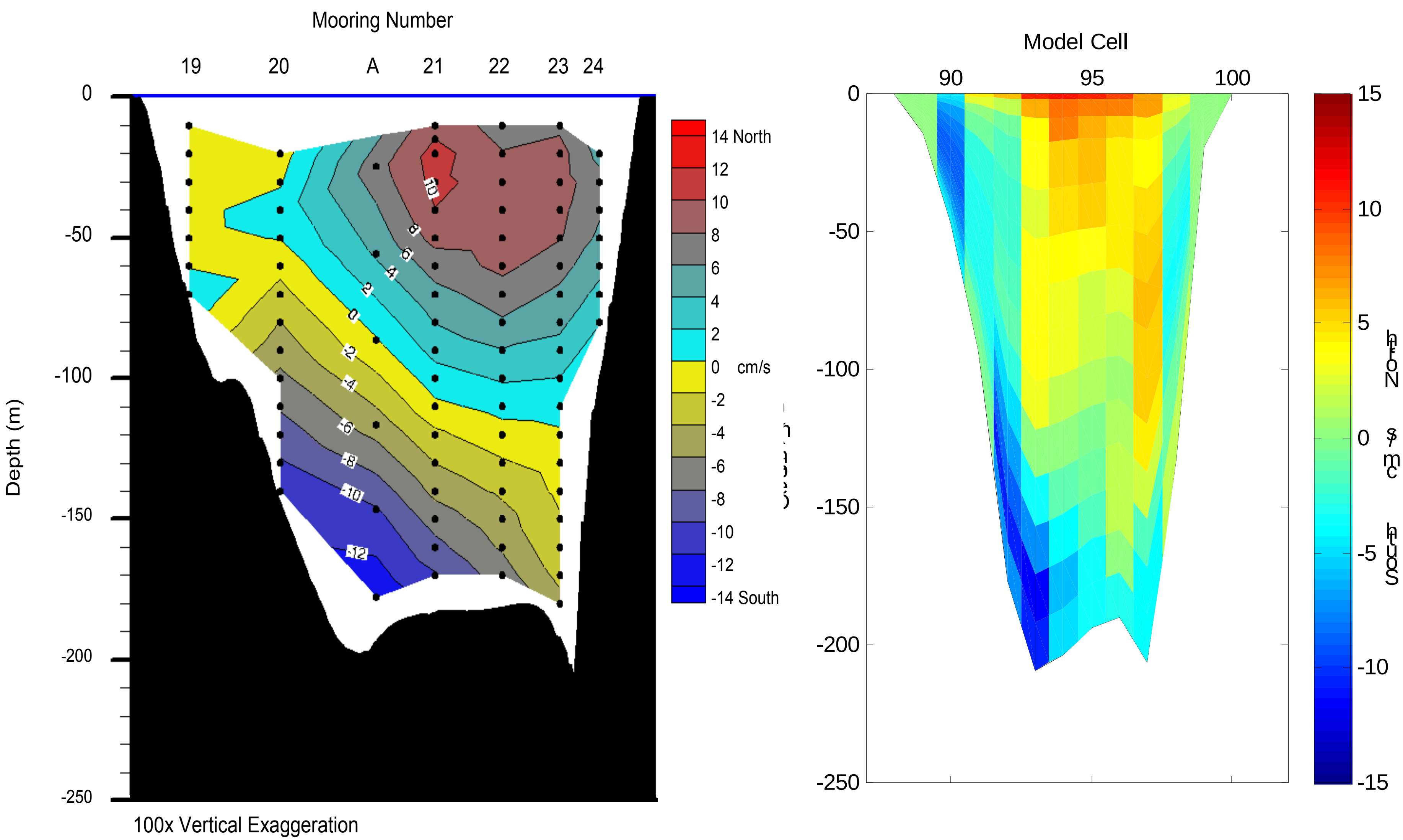
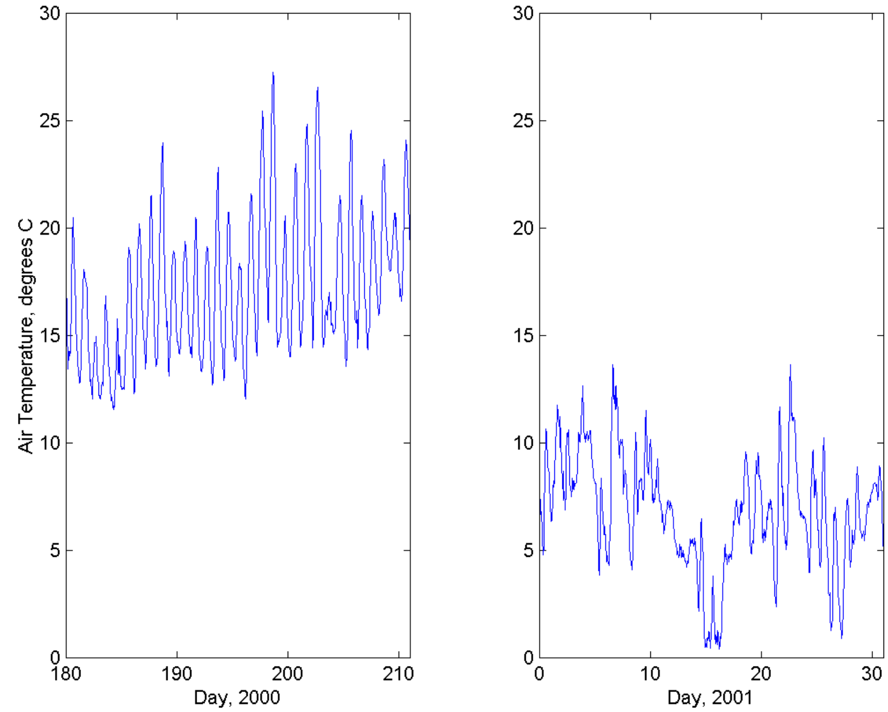


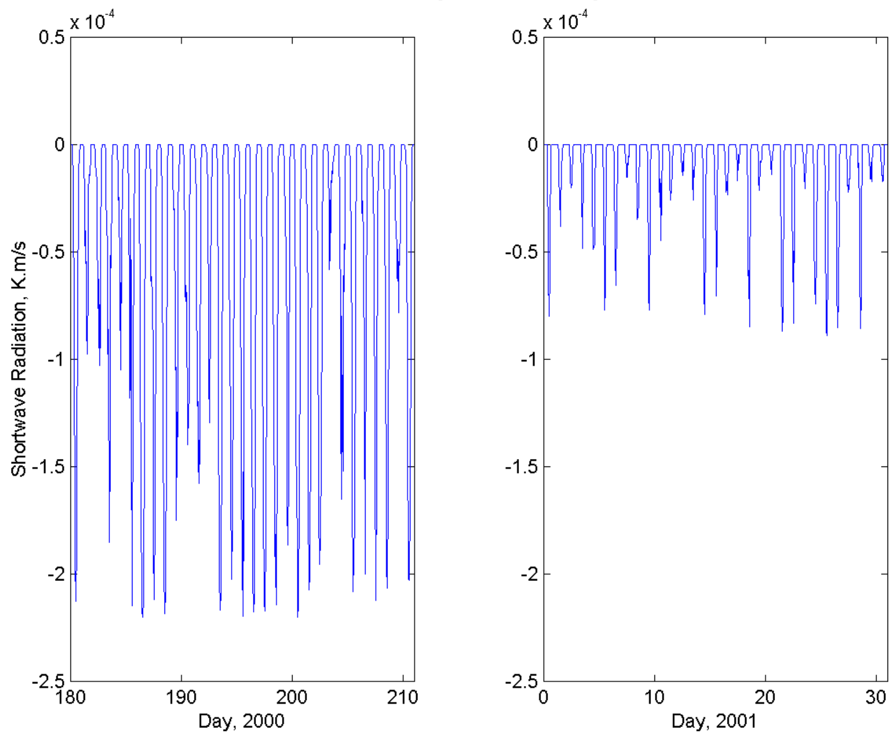
Figure 16. Mean current speeds perpendicular to Point Wells Transect (January 27-February 23, 2001; from Ebbesmeyer et al., 2002) and model predictions of mean north-south current speeds (m/s) at the same location (model cell j = 92; January 30-February 28, 2001).

Appendix A
Atmospheric Data

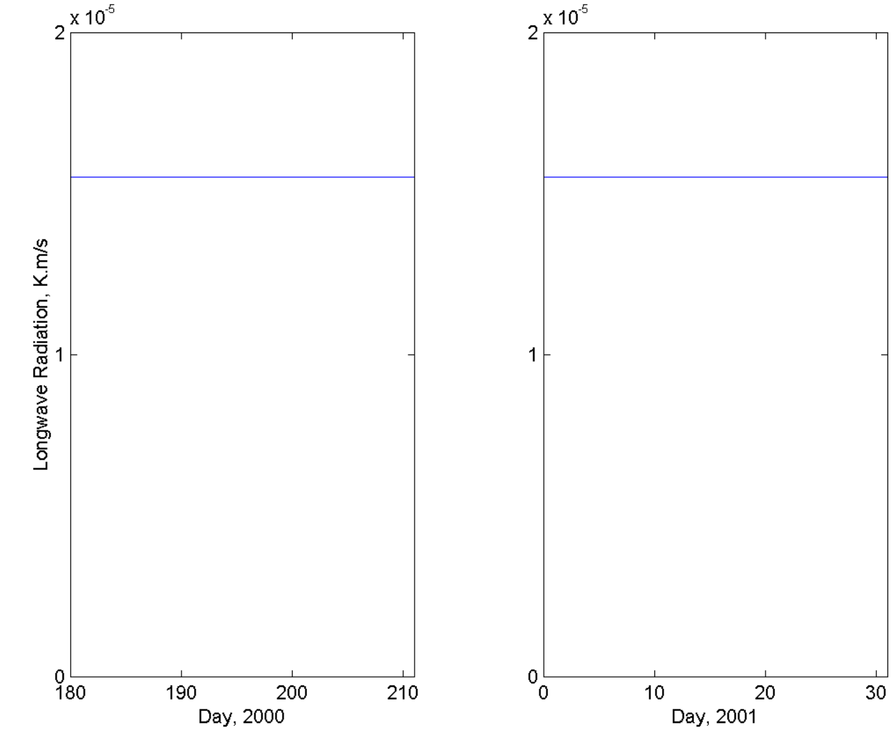
Air Temperature, July 2000 and January 2001



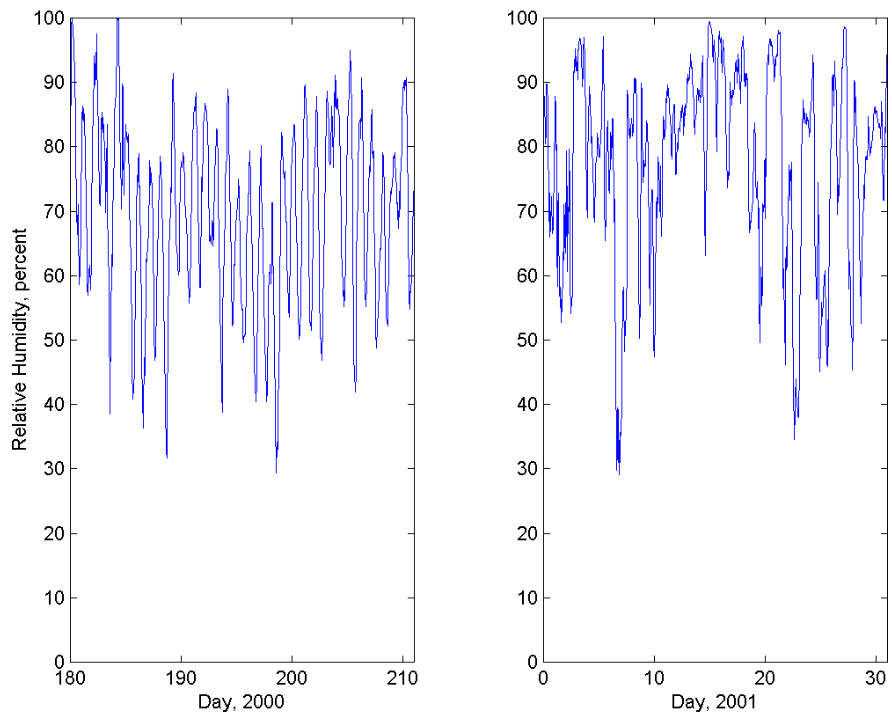
Shortwave Radiation, July 2000 and January 2001

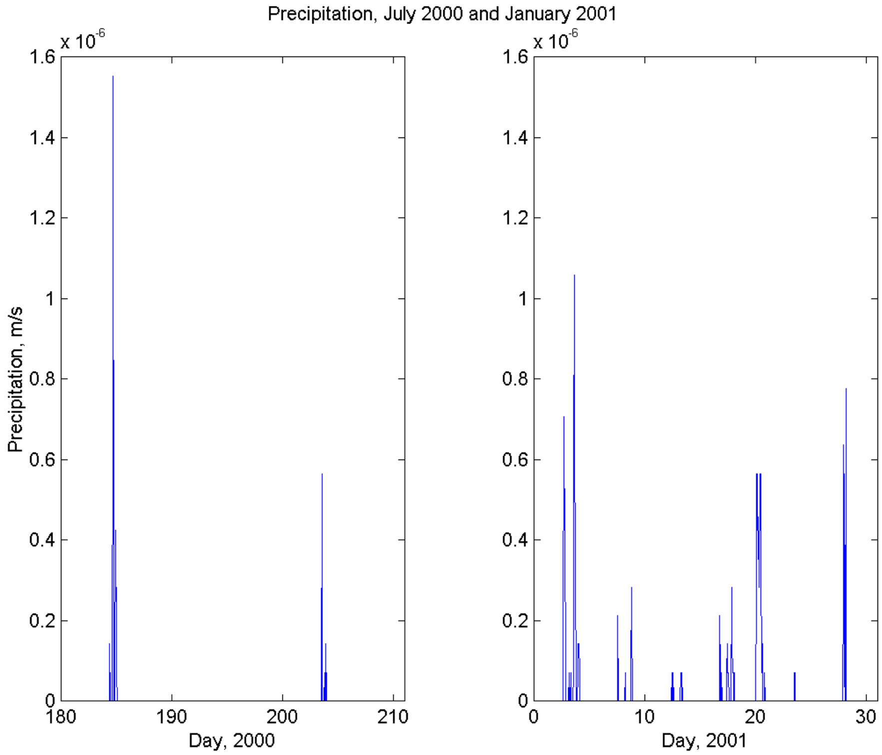


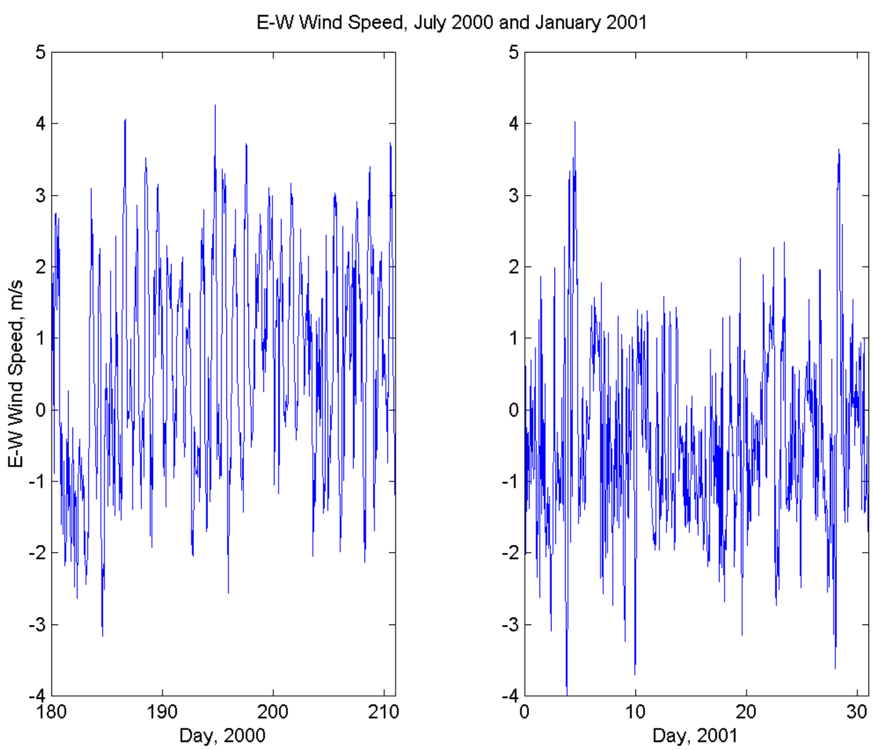
Longwave Radiation, July 2000 and January 2001

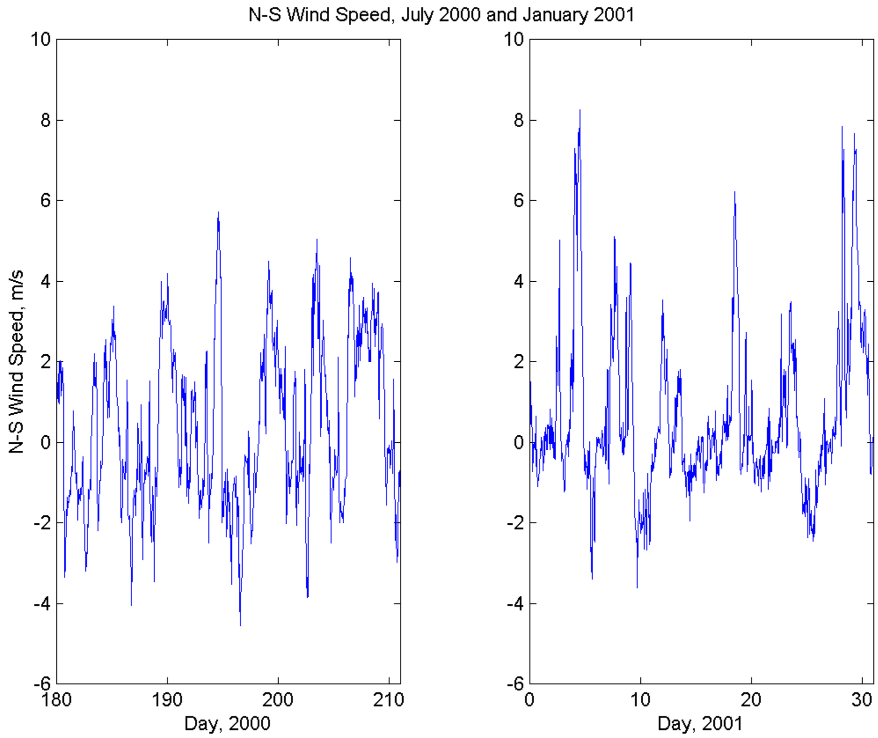


Relative Humidity, July 2000 and January 2001




Precipitation, July 2000 and January 2001
x 10^-6
Precipitation, m/s
Day, 2000
Day, 2001


E-W Wind Speed, July 2000 and January 2001
E-W Wind Speed, m/s
Day, 2000
Day, 2001


N-S Wind Speed, July 2000 and January 2001
N-S Wind Speed, m/s
10
8
6
4
2
0
-2
-4
-6
180
190
200
210
Day, 2000
0
10
20
30
Day, 2001

Appendix B

Tidal Harmonics

Appendix B
Tital Harmonics

Tidal Station		M2 Amplitude (m)		M2 phase (Greenwich)		K1 Amplitude (m)		K1 phase (Greenwich)		S2 Amplitude (m)		S2 phase (Greenwich)	
Number	Station	Data	Model	Data	Model	Data	Model	Data	Model	Data	Model	Data	Model
1	0	1.07	1.120	11.5	12.7	0.831	0.818	277.3	276.8	0.258	0.265	37.9	40.4
2	10	0.652	0.698	350	355.9	0.75	0.744	270	272.3	0.155	0.162	13.2	21.6
3	11	0.684	0.733	350.6	355.3	0.764	0.750	270.8	272.0	0.168	0.172	13	21.2
4	12	0.656	0.705	0.9	2.9	0.728	0.742	273.6	274.8	0.166	0.165	23.8	27.5
5	13	0.559	0.564	338.5	340.7	0.703	0.704	269.1	267.6	0.145	0.136	357.4	358.3
6	20	0.581	0.557	344.7	343.3	0.738	0.707	269.5	268.7	0.148	0.134	4.8	0.2
7	21	0.664	0.575	0.7	-14.4	0.756	0.714	273.7	269.4	0.17	0.137	23.1	3.7
8	22	0.968	0.736	18.1	2.6	0.817	0.772	279.7	273.9	0.24	0.172	43.5	26.3
9	5016	0.895	0.957	4.2	6.4	0.823	0.785	273.6	274.6	0.222	0.226	27.8	32.9
10	5059	0.93	0.972	4.8	7.1	0.799	0.787	275.8	275.2	0.226	0.230	29.9	33.2
11	5088	0.945	1.018	4.8	7.5	0.818	0.798	273.7	275.4	0.235	0.241	28.7	34.1
12	5246	1.031	1.107	6.1	8.3	0.837	0.817	274.3	275.6	0.225	0.264	29.1	35.0
13	5269	1.044	1.108	1.5	8.1	0.822	0.816	272	275.6	0.262	0.264	27.7	34.8
14	5293	1.035	1.110	7.4	8.1	0.823	0.817	275	275.6	0.264	0.265	33	34.9
15	5296	1.025	1.104	5.5	8.2	0.835	0.816	274	275.6	0.257	0.263	29.1	35.0
16	5441	1.083	1.174	6.4	8.9	0.853	0.829	274.5	276.0	0.271	0.281	30.2	35.7
17	5478	1.078	1.144	5.6	8.4	0.835	0.823	276.1	275.8	0.266	0.274	30	35.2
18	5526	0.94	0.994	6.4	8.5	0.8	0.798	277.4	275.5	0.227	0.234	31.2	35.9
19	5639	1.013	1.067	6	11.3	0.84	0.812	274.2	276.4	0.255	0.253	36	38.7
20	5717	1.114	1.205	15.7	15.9	0.817	0.834	281.2	278.8	0.266	0.289	44.7	44.3
21	5958	1.102	1.176	18.1	15.4	0.825	0.828	281.8	278.5	0.269	0.281	47.4	43.8
22	6025	1.09	1.142	10.9	12.9	0.823	0.823	277.9	277.0	0.279	0.271	37	40.7
23	6248	1.118	1.167	12.5	13.5	0.825	0.829	276.8	277.1	0.272	0.276	38.8	41.4
24	6254	1.13	1.199	10.9	13.5	0.901	0.833	275.8	277.0	0.272	0.285	37.2	41.5
25	6281	1.412	1.560	30	30.2	0.867	0.894	288.1	286.0	0.33	0.380	57.9	63.8
26	6451	1.318	1.448	22.3	27.9	0.945	0.875	284.5	284.8	0.327	0.349	57.9	61.1
27	6486	1.225	1.333	21.4	23.6	0.896	0.867	282.9	282.5	0.298	0.319	49.3	55.6
28	6500	1.333	1.449	27.8	27.9	0.876	0.875	283.7	284.7	0.321	0.349	57.9	61.1
29	6539	1.33	1.443	27.2	28.1	0.927	0.875	285	284.7	0.324	0.347	55.2	61.2
30	6545	1.133	1.189	13	13.4	0.834	0.828	278	276.9	0.273	0.282	38.6	41.5
31	6800	1.44	1.592	32.2	33.3	0.945	0.897	287.7	287.9	0.354	0.390	61.5	67.9
32	6828	1.34	1.455	27	28.4	0.92	0.877	284.8	285.1	0.326	0.351	56.5	61.6
33	6969	1.464	1.609	29.9	33.4	0.849	0.900	288.7	287.9	0.348	0.394	62.4	67.9
34	7265	1.043	1.092	11.9	12.8	0.829	0.814	277.8	277.0	0.26	0.258	35.9	40.3
35	7427	1.012	1.059	10.5	12.1	0.81	0.806	278.1	276.7	0.245	0.249	34.2	39.5
36	7659	1.033	1.077	10.5	12.7	0.837	0.811	277.6	276.9	0.252	0.255	35.9	40.1
37	7814	1.023	1.071	9.4	12.6	0.872	0.811	275.6	277.0	0.246	0.252	35	40.1
38	7854	0.751	0.854	3.2	6.7	0.819	0.772	280	275.4	0.183	0.200	16.8	33.6
39	7881	1.021	1.112	11.8	13.5	0.834	0.820	276.2	277.3	0.251	0.263	40.8	41.1
40	7952	1.103	1.133	12.2	13.9	0.87	0.823	276.7	277.1	0.267	0.268	37.8	41.4
41	8000	1.086	1.120	13.2	12.9	0.841	0.819	276.5	276.8	0.267	0.265	38.6	40.5

Appendix B
Tital Harmonics (Continued)

Tidal Station		M2 Amplitude (m)		M2 phase (Greenwich)		K1 Amplitude (m)		K1 phase (Greenwich)		S2 Amplitude (m)		S2 phase (Greenwich)	
Number	Station	Data	Model	Data	Model	Data	Model	Data	Model	Data	Model	Data	Model
42	8094	1.052	1.091	11.8	12.8	0.868	0.815	277.2	277.1	0.254	0.258	36.8	40.2
43	8313	1.075	1.158	11.9	12.8	0.836	0.824	278.9	276.8	0.273	0.275	35.4	40.7
44	8314	1.081	1.158	11.5	13.2	0.82	0.825	278.3	277.0	0.272	0.275	37.3	41.0
45	8315	1.114	1.187	11.2	13.4	0.824	0.830	278.2	276.9	0.278	0.282	36.8	41.3
46	8316	1.102	1.185	11.6	13.5	0.828	0.829	277.6	276.9	0.277	0.282	37.4	41.4
47	8317	1.09	1.172	10.5	14.0	0.815	0.829	277.6	277.4	0.274	0.278	36.4	42.2
48	8318	1.091	1.176	12.9	14.5	0.814	0.828	278.8	277.4	0.273	0.279	39	42.8
49	8558	0.936	1.108	29	16.6	0.81	0.823	279.8	278.1	0.248	0.263	51.3	43.8

Mean Error:	0.064	1.01	-0.016	-0.38	0.007	3.08
Abs Mean Error:	0.078	2.94	0.023	1.39	0.013	5.23
RMS Error	0.088	4.39	0.030	1.82	0.019	6.39

Tidal Station		N2 Amplitude (m)		N2 phase (Greenwich)		O1 Amplitude (m)		O1 phases (Greenwich)		P1 Amplitude (m)		P1 phases (Greenwich)		M4 Amplitude (m)		M4 phases (Greenwich)	
Number	Station	Data	Model	Data	Model	Data	Model	Data	Model	Data	Model	Data	Model	Data	Model	Data	Model
1	0	0.212	0.220	340.3	341.6	0.458	0.462	255.4	255.7	0.252	0.238	274.5	274.3	0.021	0.015	195	201.9
2	10	0.138	0.144	318.4	324.7	0.44	0.437	250	251.3	0.232	0.216	267.9	269.0		0.052		58.5
3	11	0.14	0.151	321	324.2	0.45	0.440	249.9	251.5	0.244	0.220	270.1	268.9		0.053		70.4
4	12	0.125	0.145	333.5	330.9	0.418	0.435	252.3	254.3	0.228	0.216	271.1	271.0		0.047		52.6
5	13	0.128	0.125	302.7	308.0	0.402	0.400	248.9	247.2	0.221	0.203	263.8	262.9		0.031		74.8
6	20	0.13	0.122	313.7	309.4	0.421	0.411	247.5	248.3	0.232	0.203	264.2	263.5		0.036		326.6
7	21	0.144	0.123	326	311.6	0.443	0.423	251.2	249.1	0.235	0.205	269.5	264.1		0.072		317.3
8	22	0.197	0.147	346.3	328.8	0.452	0.482	256.6	253.0	0.251	0.223	275.8	268.5		0.195		310.1
9	5016	0.183	0.191	333.1	334.9	0.457	0.446	250	253.7	0.272	0.227	271.8	272.0	0.016	0.017	178.7	165.0
10	5059	0.206	0.194	337	335.7	0.454	0.446	253.8	254.3	0.265	0.228	274.2	272.7		0.020		168.5
11	5088	0.205	0.202	334.3	336.4	0.475	0.454	251.5	254.5	0.271	0.231	272	272.8	0.021	0.026	174	172.5
12	5246	0.217	0.220	336.3	337.2	0.477	0.462	251.7	254.6	0.277	0.237	272.6	273.1	0.036	0.044	183.2	178.8
13	5269	0.194	0.220	335.1	337.0	0.474	0.462	251.7	254.7	0.272	0.237	270.5	273.1	0.029	0.044	172.6	178.2
14	5293	0.201	0.221	335.9	337.0	0.472	0.462	254.2	254.6	0.272	0.237	273.4	273.2	0.032	0.044	180.9	178.7
15	5296	0.221	0.219	336.1	337.2	0.477	0.461	251.3	254.6	0.276	0.236	272.3	273.1	0.034	0.043	179	179.8
16	5441	0.23	0.233	336.6	337.9	0.486	0.468	251.8	255.0	0.282	0.240	272.8	273.6	0.041	0.057	180	181.8
17	5478	0.213	0.227	338.9	337.3	0.466	0.465	254.2	254.8	0.276	0.239	274.5	273.3	0.042	0.051	183.2	179.9
18	5526	0.188	0.197	338	337.6	0.452	0.460	251.7	254.8	0.254	0.232	275.5	272.9	0.006	0.013	149.8	130.3
19	5639	0.205	0.212	333.7	340.3	0.493	0.461	253.9	255.1	0.278	0.235	272.7	273.8	0.02	0.016	176.2	180.2
20	5717	0.219	0.235	351.8	345.6	0.436	0.472	260.5	257.5	0.27	0.243	279.6	276.7	0.028	0.027	240.9	222.6
21	5958	0.216	0.230	350.5	345.0	0.457	0.469	257.3	257.2	0.272	0.241	280	276.3	0.026	0.021	250.8	220.7
22	6025	0.224	0.224	343.8	341.8	0.462	0.465	254.1	255.8	0.273	0.239	276.1	274.4	0.021	0.014	210.4	210.9
23	6248	0.221	0.229	347.9	342.7	0.448	0.469	255.2	256.0	0.273	0.240	275.2	274.5	0.021	0.014	208.8	213.1
24	6254	0.227	0.235	339.2	342.4	0.481	0.471	249.2	255.7	0.298	0.241	273.8	274.3	0.021	0.016	203.2	222.5
25	6281	0.265	0.294	8.5	2.5	0.435	0.511	261	264.1	0.285	0.263	286.1	285.1	0.041	0.058	306.8	304.8
26	6451	0.225	0.275	358.4	360.0	0.482	0.501	258.3	263.1	0.313	0.258	282.5	283.8	0.03	0.037	283.2	302.0
27	6486	0.238	0.255	354.5	354.5	0.502	0.510	258.8	261.1	0.296	0.256	281.1	280.7	0.058	0.042	35.7	34.6
28	6500	0.267	0.274	8.5	359.9	0.437	0.500	261.6	263.0	0.287	0.258	282	283.7	0.032	0.036	272.8	302.6
29	6539	0.249	0.273	356.2	0.1	0.479	0.501	257.1	263.0	0.307	0.258	282.9	283.8	0.032	0.035	286.4	302.2
30	6545	0.236	0.233	343	342.7	0.465	0.468	254.8	255.6	0.276	0.241	276.3	274.4	0.02	0.016	207.2	231.5
31	6800	0.262	0.299	0.8	6.3	0.483	0.514	259.1	265.9	0.313	0.265	285.6	287.2	0.047	0.065	302.6	313.7
32	6828	0.253	0.275	1.8	0.4	0.464	0.501	257.8	263.4	0.304	0.258	282.8	284.1	0.033	0.038	283	304.8
33	6969	0.275	0.302	3.2	6.4	0.463	0.516	265.1	265.9	0.255	0.266	286.3	287.2	0.055	0.070	291	312.4
34	7265	0.204	0.215	344.4	341.5	0.446	0.462	253.2	255.9	0.275	0.236	276	274.3	0.021	0.016	200.8	194.1
35	7427	0.199	0.209	341.2	340.8	0.444	0.457	253.8	255.6	0.268	0.234	276.3	274.0	0.023	0.017	193.6	182.0
36	7659	0.206	0.213	342.6	341.6	0.444	0.459	254.3	255.8	0.277	0.235	275.9	274.3	0.02	0.018	184.7	182.8
37	7814	0.201	0.212	341.2	341.5	0.464	0.459	250.4	255.8	0.288	0.235	273.7	274.4	0.02	0.016	187.2	186.2
38	7854	0.133	0.173	333	335.5	0.41	0.447	241.8	254.7	0.271	0.225	277.1	272.3	0.047	0.018	351.3	76.8
39	7881	0.179	0.220	341.6	342.4	0.421	0.464	250.3	256.1	0.276	0.238	274.3	274.7	0.019	0.022	24.2	185.0
40	7952	0.217	0.225	344.4	342.8	0.481	0.465	250.7	255.8	0.287	0.238	274.8	274.4	0.02	0.024	172.4	184.2
41	8000	0.2	0.221	340.9	341.8	0.494	0.463	255.5	255.7	0.278	0.237	273.7	274.2		0.015		196.9
42	8094	0.183	0.216	351.3	341.6	0.478	0.462	250.5	255.9	0.287	0.236	275.2	274.5	0.019	0.020	186.6	183.5
43	8313	0.208	0.228	339.9	341.7	0.46	0.466	253.2	255.6	0.274	0.239	276.3	274.2		0.016		211.6
44	8314	0.205	0.227	340.4	342.1	0.468	0.467	254.9	255.8	0.269	0.239	275.9	274.3		0.015		212.5
45	8315	0.211	0.233	340.8	342.2	0.471	0.470	254.6	255.7	0.27	0.240	275.9	274.2		0.015		219.4
46	8316	0.208	0.232	341.2	342.3	0.466	0.470	254.4	255.7	0.271	0.240	275.3	274.3		0.016		227.4

Appendix B
Tital Harmonics (Continued)

47	8317	0.204	0.229	339.5	343.2	0.463	0.467	254.1	256.1	0.267	0.240	275.1	274.8		0.020		232.1
48	8318	0.204	0.230	341.8	343.8	0.463	0.466	255	256.0	0.267	0.240	276.3	274.9		0.021		236.2
49	8558	0.195	0.221	347.8	345.1	0.46	0.465	261	256.8	0.268	0.238	278.4	275.5	0.006	0.020	173.9	203.8
Mean Error:			0.013		-0.60		0.006		2.17		-0.034		-0.78				
Abs Mean Error:			0.017		3.31		0.018		2.77		0.035		1.51				
RMS Error			0.021		4.77		0.024		3.62		0.037		2.05				